MANAGEMENT STRATEGIES FOR A BOREHOLE RESIN PRODUCTION SYSTEM IN SLASH PINE

By

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Abstract of Dissertation Presented to the Graduate School
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A new process is described for production of oleoresin from slash pine (*Pinus elliottii*) by means of borehole wounds to the tree's xylem. Advantages of this process over conventional gum resin production methods include higher labor productivity, improved product quality, reduced tree stress, and reduced insect pest problems. Resin yields averaged 650 g per borehole, or nearly 1.7 kg per tree with multiple boreholes, in tapping experiments conducted from 1991 to 1994 in Florida and Georgia, USA. Borehole yields were generally more variable than for conventional gum resin production. Yields were significantly affected by tree size, and experimental treatments for borehole diameter, depth, number, spacing, horizontal and vertical orientation and spacing, chemical stimulants, and collection container type. Yields were highest for borehole treatments during the midsummer period (August), but did not differ at other times of year. Resin flow from a single tapping treatment continued over a period of several months, and was well-described by a negative exponential function of time, with 90 percent of cumulative seasonal flow attained at 120 days after treatment. Tree growth rates were not measurably altered by borehole tapping. A systems model of borehole resin

production was conceptualized in terms of closed-channel hydraulic flow under hydrostatic pressure gradients, and a system architecture of the resin duct network that gives rise to predictable patterns of oleoresin drainage. Tree basal area was used as an indicator of preformed oleoresin storage capacity, and resin yields per unit cross-sectional area of the tree stem were modeled as a function of tapping treatment extent and intensity. Management strategies and borehole treatments were designed to maximize borehole yields by controlling tapping treatment intensities. At the optimal treatment level, predicted yields ranged from 1520 to 3100 g for trees 23 to 37 cm dbh, respectively. A mechanized borehole production system was developed, including a mobile multiple-spindle drilling system, and a spout-bag container apparatus. Field tests of the mechanized system operation demonstrated a capacity of 59 trees per hour, representing a 50 percent increase in labor productivity over non-mechanized systems.

INTRODUCTION

The Borehole Resin Production System

In 1990, a new technique for producing oleoresin from living Slash pine trees (*Pinus elliottii*) was discovered by longtime gum resin farmers in Georgia USA, and subsequently developed by researchers (Hodges and Williams, 1993). The borehole tapping process essentially involves drilling holes into the xylem to open resin ducts and provide a pathway for their drainage into a closed collection device. Various commercial and experimental devices have been described for collecting resin from small punch wounds to the bark, essentially as a bark-chipping treatment (Low and Abdul Razak, 1985; Ostrum, 1946; Kraus, 1965); however, no previous reports of a borehole tree exudate production system have appeared in the English literature.

A typical borehole treatment pattern for a tree is depicted in Figure 1.1. The borehole treatment process consists of drilling several holes 2.5 cm in diameter by 7.6 to 17.8 cm deep (1 by 3 to 7 inches). Boreholes are placed approximately 10 cm above ground level, in trees at least 15 cm diameter at breast height (dbh). Chemical treatments of sulfuric acid (H_2SO_4) and CEPA are sprayed inside boreholes to improve yields, as with conventional open-face tapping methods. Resin flows from the borehole into an attached collection device, beginning immediately after treatment, and continuing for a period of several months. The prolonged flow from boreholes is a key feature of this system. The borehole system represents a logical extension of the evolutionary trend in gum resin production systems toward

internalization of the wounding process. Originally, the production system concept was demonstrated as an atmospherically sealed collecting resin with 2-liter PET bottles screwed directly into boreholes using their cap threads (Hodges and Williams, 1993), as shown in Figure 1.2.

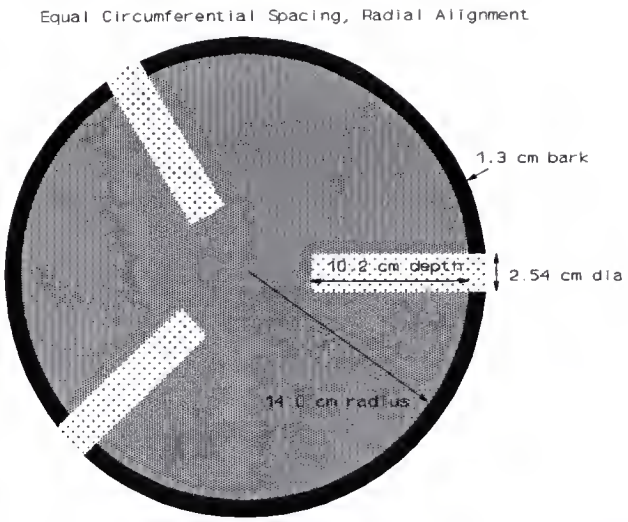

Figure 1,1. Hole configuration for borehole resin production method, shown in cross section of the tree's stem.

Resin production from borehole tapping is highly variable and species specific, presumably reflecting genetic differences. Tests with other species used commercially for gum resin production did not produce appreciable yields, including the sympatric species longleaf pine (*Pinus palustrus* Mill) in the southeast US. Borehole resin yields from slash pine are also sensitive to tapping treatments.

The borehole production system has several important economic, ecological, and technological advantages compared to conventional gum resin production systems. First, the labor productivity of borehole tapping is several-fold greater than conventional methods because of the higher product yield per human intervention. The average borehole yield per tree is equivalent to that obtained from 4 wounding treatments with the conventional open-face bark chipping method. Reduced oxidation and gross contamination of the resin collected in a closed container results in a higher quality product. Laboratory analysis of borehole-produced resin showed that it had a higher composition of preferred resin acid species, and a higher chemical reactivity, which is valuable for manufacturing synthetic resins and

blending (Akzo Coatings, Baxley GA). Capture of volatile terpenes by the closed container means greater recovery and less emission of volatile attractants for bark beetles, so pest problems are generally reduced, but not eliminated in borehole tapping. Because borehole wounds cause relatively little damage to the tree's bark and cambium tissue, it is expected that there is less disruption of its normal growth processes, although water transport in the xylem may be impaired. Boreholes are typically covered by new cambium and bark within about 2 years, and the tree may be allowed to continue growing without distortion of its form. Since boreholes are made near ground level, there is little or no damage to the merchantable part of the tree.

The borehole resin production system for slash pine represents a renewable resource for high quality industrial materials that is sustainable and environmentally benign. The slash pine resource in 8 southeast US states was estimated at 12.8 x 10^6 ac, with 11.6 x 10^9 ft^3 growing stock, annual growth of 1.1 x 10^9 ft^3, and annual removals of 675 x 10^6 ft^3 (Sheffield et al., 1983). Much of the resource is now intensively managed, and as the pulp and paper industry continues to develop capacity for using recycled fiber, and demand for virgin wood fiber is reduced, there will be additional high quality resources available for resin production. There exists a strong world market for pine chemical products in industrialized countries, with large import volumes to the United States (Pombo, 1994). Borehole-produced oleoresin from slash pine is a high quality, value-added non-wood forest product that is compatible with complete utilization of the tree for wood products and other forest management objectives. The borehole system can potentially generate greater economic benefits from pine timber resources, and offer economic incentives for extended forest rotation periods.

Figure 1,2. Two-liter PET bottle used for collection of oleoresin from boreholes in slash pine.

Ecology and Natural History of the Pine Resin System

Management of resin production systems is fundamentally based upon appropriate manipulation of the pine tree's chemical defensive behavioral response. Resins, tannins, phenolics, alkaloids and other secondary compounds evolved in the higher plants as physico-chemical defense mechanisms against herbivorous predators, decomposer microorganisms, and mechanical injuries. Many diverse groups of trees convergently evolved similar structural patterns in their defensive systems based upon a generalized process of wound compartmentalization to isolate injured tissues and prevent the spread of decay (Shigo, 1979). In the coniferous trees (Coniferales), specialized resin ducts arose to produce and store natural resins throughout the stem, branches, and leaves, as a proactive defensive strategy. The resin system reached its greatest development in the pine family (Pinaceae), and its productivity is a key adaptation underlying the success of this plant group throughout the world under harsh environmental conditions of seasonal drought, low nutrient availability, and periodic fire. Productivity of the pine's carbon-based chemical defense system is less limited by site quality than are nitrogen-based defense systems, enabling the tree's survival in marginal habitats, and will likely confer a selective advantage to pines under conditions of global climate change, with elevated CO_2 levels providing increased substrate for resin formation.

Pine resin consists of a complex mixture of compounds that impart different chemical and physical properties and functions to the whole oleoresin (Hodges et al., 1977). Diterpenes, or resin acids, are double carbon-ring compounds constituting approximately 70 to 85 percent of the mass of oleoresin, while monoterpenes are simpler single carbon ring volatile compounds that make up the

essential oil of turpentine (Zinkel, 1981). The terpenes are toxic to insects and microorganisms, and render woody tissues less digestible to herbivores. The terpenes exist in phase equilibrium, with the chemical composition of resin acid species and the overall monoterpene concentration determining whether the whole oleoresin is a solid or liquid. Solidified and hardened resins impart structural strength to the wood matrix and act as a mechanical barrier against growth of lesions. Insect pest pressures on pines in the Southern US are very high, and oleoresin flow rates and duration are the best predictors of host tree resistance to beetle attack for the southern pines (Hodges et al., 1977, 1979).

Ecological studies of the pine oleoresin defense system against bark beetle attack have demonstrated complex dynamic behavior patterns between the tree host and attacking herbivores (Sharpe et al., 1987, 1985; Blanche et al., 1983; Hodges et al., 1979). The theme of these models is that different levels of tree stress factors, such as drought, insect attack, or infection of decay-causing microorganisms, activate varying responses by the host tree. Terpene emissions by the tree act as attractants to beetles by signaling its vulnerability. Moderate levels of combined stress stimulate production of terpenes, but excessive stresses may overwhelm defensive mechanisms and lead to tree death.

Anatomy and Physiology of Oleoresin Production

Preformed oleoresin is distributed throughout the tree and constitutes about 2 to 5 percent of the dry weight of sapwood and 25 to 40 percent of heartwood in slash pine (Koch, 1972). It is manufactured by the specialized resin canal epithelial cells, and secreted into the lumen formed by their continuous tubular organization. These resin ducts are arranged and interconnected as a network that allows

transport of resin both longitudinally and radially in the stem of the tree, as shown in Figure 1.3.

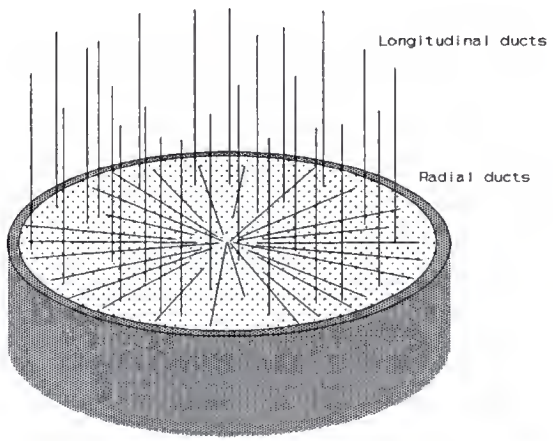

Figure 1,3. Illustration of pine oleoresin system.

Ducts range in size from 20 to over 200 microns in inside diameter, and 0.2 to over 1 m length (Koch, 1972). Radial resin ducts averaged 54 microns in diameter, at densities of 50 to 90 cm^{-2} in tangential sections, with lower densities in outer sapwood layers (Mergen and Echols, 1955; Hodges et al., 1981). The vertical resin ducts are larger, and occur at densities of 30 to 50 cm^{-2} (Koch, 1972).

Preformed constitutive oleoresin stored in the duct system is maintained at hydrostatic pressures as high as 13 atmospheres (Bordeau and Schopmeyer, 1958) which serves as a potential energy source to drive oleoresin flow for mobilization to sites of attack or injury. Resin flow in the ducts is a function of temperature and viscosity, size and length of ducts, and the pressure differential between source and sink regions (Schopmeyer et al., 1954). Oleoresin viscosity is inversely related to ambient temperature. Evaporation of monoterpenes upon exposure to the atmosphere at a wound site brings about a supersaturated state which leads to crystallization of the resin acids. Crystallization may also be the immediate cause for occlusion of resin ducts, stopping resin flow to the environment.

Synthesis of oleoresin occurs to fill new resin ducts formed as the tree grows, and in response to stresses. Resin acids in oleoresin cannot be remetabolized or "turned over," so their production is an investment by the tree (Lawrence, 1971). Newly synthesized oleoresin makes-up for the translocated

preformed resin deposited at wound sites, and may also be manufactured immediately at wound sites. The mechanism responsible for the induced resin production response is not well understood, but may be mediated by pressure or osmotic balance between the resin canal epithelium and the extracellular oleoresin storage compartment, and influenced hormonally by plant regulators such as ethylene (Wolter and Zinkel, 1984). Synthesis of oleoresin in the tree competes with growth processes for the common pool of carbohydrate precursors (Lorio and Sommers, 1986), and the balance between growth and differentiation processes is a species-specific trait (Lorio, 1986). Because the monoterpenes are energetically less costly to produce than diterpenes by virtue of their lower molecular weight, they may be preferentially synthesized under stress conditions (Paine et al., 1987).

Economics of Commercial Resin Production and Utilization

Production and use of resinous exudates from coniferous trees has been an important economic activity in many parts of the world for millennia (Hillis, 1987, Gamble, 1921). Early civilizations of the Middle East region first used natural tars for building water-tight wooden-hulled sailing vessels; this later lead to the development of naval stores as an industrial commodity for European empires. Modern uses of conifer resins include adhesives, sealants, inks, coatings, solvents, cleaners, antiseptics, insecticides, flavors and fragrances (Zinkel and Russel, 1988). In commercial use, the monoterpenes and diterpenes are normally separated by steam distillation to produce turpentine and solid rosin, respectively, as the basic commodities. Utilization of gum resin in industrialized economies has followed a trend toward greater fractionation and processing for derivative products of higher value.

Commercial gum resin production began in the Southern United States in the 1600s, and continued to expand until reaching a peak of 4.1×10^5 metric tonnes (Mg) in 1910, then declined due to rising labor costs and exhaustion of timber resources (Gamble, 1921), and production is now less than 1000 tonnes. Offsetting this decline in the US, the industry rapidly developed in many other tropical and sub-tropical areas having pine forests, with some 26 different species used commercially (McReynolds et al., 1988). China, Indonesia, Brazil, Argentina, Mexico, and several smaller African and Central American countries, are now the principal producing countries for gum resin, with current world production at approximately 4.5×10^5 Mg annually, having a value of $\$200 \times 10^6$ (Naval Stores Int. Yearbook, 1992). Imports to the US amount to 18×10^6 Mg, at a total value of $\$11.3 \times 10^6$, or $\$630\ Mg^{-1}$. Gum rosin produced from slash pine in the United States is a premium product, with a market value 30 to 40 percent greater than other rosins, and is typically blended with other materials to make value-added modified resins.

Gum resin products compete directly with other sources of pine chemicals obtained by solvent extraction of resinous wood, or tall oil recovery in paper mills, and indirectly with petroleum derivatives (Stauffer, 1988). Increased production of wood rosin and tall oil rosin in the US has offset the decline in gum rosin, and lead the US to continue growing as the largest consumer of pine chemicals (Pombo, 1994).

Technology Development in Gum Resin Production Systems

All gum resin production systems involve some means of artificially wounding the pine tree to open the resin canals and allow oleoresin to drain into a collecting device. Two trends have occurred in the evolution of technology for

producing gum resin: tree conservation for maximization of long-term tree productivity through reduced physiological damage of wounding treatments, and increased labor productivity with treatments to prolong gum flow through internal progressive wounding action. The modern era of gum resin production began in the mid-1950's with the advent of bark-chipping and chemical treatment methods, which are now practiced worldwide. This production system entails cutting-away strips of bark 1 to 5 cm high at regular intervals of 1 week to 1 month during the warm season, and applying a stimulant chemical solution to the upper ledge of freshly exposed bark and cambium on the chipped face of the tree. Chemical treatments have dramatically improved the productivity of gum resin tapping operations by simultaneously increasing yields and reducing labor requirements. Repeated wounding treatments are necessary to remove resin-saturated bark and phloem tissue, but chemical treatment with sulfuric acid (H_2SO_4) prolongs the period of resin flow by slowly diffusing to wound fresh tissue (Ostrum et al., 1958). The bark-chipping method allows sustained production for an extended period. In the southeast US, trees are tapped up to 8 months for 8 years, with two faces equal to one-third the tree's circumference in width.

The latest generation of gum resin production technology involves stimulation of the pine tree's resin biosynthetic process with plant regulators (Kossuth, 1984). Applications of 2-chloroethyl-phosphonic acid (CEPA) stimulate resin synthesis through the action of its breakdown product ethylene gas, increasing yields up to 36 percent (McReynolds and Kossuth, 1984, 1985). The extent to which new resin synthesis can be induced by artificial treatments strongly affects the economic productivity of gum resin tapping.

Insect pest pressures from pine bark beetles (*Dendroctonus* spp, *Ips* spp.) are severe for conventional open-face gum resin production in the US. Preventative

spraying with persistent carbamate insecticides is routine, and costs for pest control represent a substantial share of total production costs (Merkel, 1981). Most countries where exotic pines have been planted do not have serious insect problems for gum resin production.

In response to rising labor costs in the US, mechanized systems were developed for the chipping operation, including a hydraulic reciprocating hack (Shaw and McReynolds, 1985), a rotary chipping tool powered by a chainsaw engine (Clements and McReynolds, 1977), and a tractor-mounted chipper for streaking trees in plantation stands (Sanders, 1974). However, none of this equipment was adopted by the industry because of poor reliability or performance compared to the traditional hand tools. Light weight hand chipping tools enable proficient workers to chip and treat 400 to 800 trees per day (Clements, 1973).

Improvement of gum resin collection systems in the US has focused on developing durable containers with chemically inert materials (e.g. HDPE plastic, aluminum) to avoid contaminating the product. High product losses may occur from overflow of open collection containers (Hodges and Shoup, 1989). Disposable paper bags were explored as a convenient, large capacity, efficiently handled container (Chappel and Harrington, 1971), but the extreme fluidity of slash pine resin resulted in a large amount of leakage and product loss. In Brazil, Argentina, and Venezuela, plastic bags are successfully used for resin collection, in both reusable and non-reusable systems.

Productivity and Behavior of Oleoresin Production Systems

Extensive knowledge about conventional gum resin production systems offers the best insight into the key factors affecting productivity and behavior of the borehole resin production system. Pine species tapped for gum naval stores

differ substantially in their productivity under typical commercial tapping, from 1 to 5 kg per tree annually with a regime of multiple treatments (Greenhalg, 1982). Resin yielding ability is a highly heritable trait. Oleoresin exudation pressure and terpene composition are heritable traits strongly correlated with oleoresin yielding ability (Bordeau and Schopmeyer,1958; Barrett and Bengston, 1964; Squillace, 1971). A genetic improvement program for slash pine resulted in a 65 percent gain in resin yields (McReynolds and Gansel, 1985). The two principal southern US pine species used for gum production, longleaf and slash pine (*P. palustrus, P. elliottii*), have remarkable differences in resin qualities, and divergent sensitivities to yield enhancing treatments (Kossuth, 1984).

Slash pine is a favored species for its high resin production, and has been widely planted and used for this purpose in Brazil, Argentina, New Zealand, South Africa, and Zimbabwe. Yields for slash pine in its native range in the southeast United States averaged about 7 kg annually from a typical 10 inch DBH tree, with a regime of 8 monthly streaks, using the best available CEPA paste treatment formulation (McReynolds and Kossuth, 1984). Physiographic conditions interact with genetic resin yield factors, and annual resin yields from slash pine planted in tropical regions have been reported equal or lower than in the US (Young, 1981; Taylor, 1985). Labor productivity of typical commercial gum resin production operations in the southeast US was estimated at 43 kg per man-hour, including labor for both the chipping and harvesting operations, using a discrete-event simulation approach (Hodges and Shoup, 1989).

Descriptive studies of commercial oleoresin yields have confirmed the dual nature of resin production from two sources: preformed oleoresin stored in the resin duct system, and newly synthesized oleoresin. Initial yields of oleoresin depend mainly upon the supply of preformed oleoresin, and tree stem diameter is the most

reliable predictor of first-year yields. Yields are also related to the area of tissue wounded, with larger stem surface area wounds resulting in higher yields, but declining amounts per unit area (Snow, 1954). Resin flow was reported greatest from the region of wood near the edges of the naval stores bark-chipped face (Larson, 1955).

Resin production over an extended period of several years is influenced by the supply of newly synthesized oleoresin, with yields during a second or third year often greater than for the first year, due to the formation of traumatic resin ducts above the worked face (Gerry, 1935). As indicators of photosynthetic capacity, tree canopy and wood volume growth rate are reliable predictors of long-term yields (Snow, 1954; Schopmeyer and Larson, 1954). The stimulant chemical CEPA appears to exert its effects over an extended period by activating new resin synthesis, with the greatest enhancement of production during the latter part of the season (McReynolds and Kossuth, 1984, 1985). CEPA appears to preferentially stimulate production of monoterpenes (Kossuth and McReynolds, 1987).

Investigations of resin flow over time from conventional gum resin production have shown that flow rates are highest immediately after chipping/acid treatment, then decline exponentially and reach a negligible level within 4 weeks (McReynolds and Kossuth, 1984; Harper and Wyman, 1936). Flow rates are related to air temperature, with substantial flow occurring only during periods when average daily temperature exceeds 20 deg. C, and maximum flow occurring during the months of July and August in the southeastern US (Harper and Wyman, 1936; Clements, 1961). Flow rates respond to seasonal temperature variations most strongly on the first day following chipping/acid treatment, and become less sensitive over time.

Empirical investigations of the effect of conventional gum resin tapping on growth rates in slash pine have shown highly variable results, with measured reductions in growth ranging from zero to 26 percent of normal growth rates, depending upon the type and intensity of tapping treatments (Schopmeyer, 1955), and genetic strain (Franklin and Gansel, 1975). These studies showed that the impact of resin tapping varies over time, causing greater growth reduction later in the season and in subsequent years of production. This finding is consistent with a model of resin production as a dual process: an initial period of draining preformed oleoresin from the resin ducts at high potential flow, then a period of new resin production from carbohydrate reserves. According to the theory of carbohydrate partitioning, it is expected that the latter phase of this process would result in reduced tree growth. To the degree that any resin tapping process activates the tree's defensive response, it could cause slowed growth. On the other hand, if the tapping process merely drains preformed oleoresin from physiologically inert stores, there may be little effect on tree growth.

Related Tree Extractive Production Systems

Insight into the nature of the borehole resin-tapping system is also available from a similarly internalized resin production system concept, developed as a one-time treatment to stimulate resin deposition in the stemwood of pines for recovery during processing at pulp mills (Stubbs, Roberts and Outcalt, 1984). This "lightwood" production system involved treating the tree with Paraquat™ or related herbicides by means of bark streak, frill, or borehole wounds, to cause a generalized wound response, and necrosis of the resin duct system over a period of 6 to 18 months. Extensive resin saturation of the xylem up to 5 m above the treatment site resulted in a 4-fold increase in oleoresin content of the tree stem on a whole tree

basis (Brown and Pienaar, 1983). This production system was not adopted commercially due to massive insect attacks and high tree mortality as a consequence of severe tree stress by herbicide injury.

The pattern of resin deposition caused by herbicide injury is relevant to the borehole tapping system. Notably, resinosis always occurred in a pie-shaped sector area, following the structure of the ray parenchyma and radial resin canals. The extent of resinosis was especially variable in height above and below the treatment site, presumably due to variation in transport of herbicide in the transpiration stream. Ingenious experiments which isolated the xylem from the phloem demonstrated that the source of oleoresin for resinosis is within the locally injured tissue, not translocated from other parts of the tree stem (Wolter and Zinkel, 1984). A preferred method for applying the herbicide to maximize resin production specified drilling multiple equally-spaced boreholes at tangential and vertical angles, such that approximately one-half of the tree's radial rays were intersected (Brown and Enos, 1976). The chemical CEPA also caused resinosis, both alone and synergistically with Paraquat (Roberts, 1983). CEPA treatments in borehole wounds to the stump caused resinosis in a region approximately 0.9 m above and 0.3 m below the treatment site (Kossuth and Koch, 1989).

The Maple sugar industry in the Northern US and Canada is the closest example of a borehole production system for collection of exudates from living trees (NEFES, 1981). Although the maple sap system is completely different physiologically from the pine resin system, there are remarkable similarities in the defensive behavior of trees in response to tapping treatments, which gives insight to the dynamics of tree borehole exudation. The pattern and intensity of multiple tapholes drilled in the maple tree affects the local supply of sap and the pressure potential of exudation. If the tree is "overtapped" with too many tapholes, yields

decline and extensive deposition of defensive chemicals occurs in the heartwood zone (Walters and Shigo, 1978). The technological developments of tubing collection systems and vacuum pumping (at 0.3 atm) resulted in a nearly four-fold increase in sap yields, demonstrating a controlling effect of pressure potentials (Walters, 1978).

PROBLEMS AND OBJECTIVES FOR MANAGEMENT OF THE BOREHOLE RESIN PRODUCTION SYSTEM

The concept and technical feasibility of the new borehole resin tapping technology was demonstrated in field tests which showed that economically attractive yields were obtainable from Slash pine, but irregular results made unclear the potential range for its application. So, a first objective of this research was to broadly characterize the nature of borehole resin production with respect to different species, site conditions, and weather patterns. Development of a conceptual working model of the borehole resin production system was a research objective to support continued technology innovation and management, through an understanding of fundamental controlling factors.

Maximization of resin yields is a primary goal for management of all gum resin production systems, in order to achieve high productivity and utilization of labor and forest resources. High variability in borehole resin yields suggested that there was a substantial potential for yield improvement through appropriate resource selection and tapping treatment design. Therefore, an objective for this work was to determine tapping treatments, resource factors, and environmental conditions which maximized resin yields.

The high level of variability in borehole resin yields also represented a problem for system management in terms of process reliability and the ability to detect process shifts in response to changes in treatments or environmental conditions. From the standpoint of industrial process engineering, it was concluded

that the borehole resin production process was "out of control". Therefore, an objective for this work was to establish a greater degree of operational control over the borehole tapping process. Increasing the reliability of predicted yields required developing an accurate statistically predictive model of resin production, with the goal of minimizing variability about the expected value as well as maximizing yields.

The borehole production system is sensitive to tapping treatments, and determination of the best combination of these treatment factors for maximizing yields is an essential task for management of the system. Borehole depth, diameter, and orientation, chemical treatment levels, and number and spacing among multiple boreholes are possible parameters for manipulation. An objective of this research was to experimentally measure the effects of various treatment levels and treatment combinations on resin yields.

Analysis of borehole tapping productivity required development of standardized equivalent measures of yields and tapping treatment intensities. Of particular interest is to describe yields in terms of the areal extent of tapping treatments, in order to evaluate economic tradeoffs for treatment strategies. An area-based model of resin production in the tree's stem was developed to express yields on a unit area basis, and to represent tapping intensity as a function of the proportion of the tree's cross sectional area tapped.

Selection of suitable forest tracts is a key area for management of the borehole resin production system. Experience with the conventional gum resin production system and early borehole tapping studies showed that tree size was an important factor affecting resin yields, and is probably the best single indicator of resource quality for borehole tapping. Although large diameter timber is more productive for borehole resin tapping, it has a higher economic opportunity cost (rental price) due to its greater value for wood products utilization, and is

associated with a greater risk of damage. The economic rental price of timber for resin production is expected to shadow general timber market prices, and the supply of high quality softwood timber is expected to become increasingly scarce over the long run (USFS, 1982; Ince, 1994). Assessment of borehole resin productivity as a function of tree size was therefore an objective of this research. Determination of the minimum acceptable tree size has consequences for the overall supply of timber available for tapping.

It is likely that the tapping treatment conditions which maximize borehole resin yields will interact with different levels of resource quality, such that the best treatment for a small trees will differ from the best treatment for large trees. However, adjustment of treatment procedures on a tree-by-tree or tract-by-tract basis is associated with a higher management cost than for a uniform treatment regime. Determination of the single best treatment for maximizing yields for all tree sizes was a goal for this research, along with assessment of the value of a condition-dependent flexible borehole treatment strategy.

In temperate zones, resin production follows a seasonal cycle, with highest flow rates occurring during the warmest period. The seasonality of resin production is important for management to organize and schedule tapping and collection operations to achieve a high level of labor and capital utilization. To the extent that production departs from an ideal of a year-round steady state, there exists some inefficiency in resource utilization. An objective for research was to measure the seasonality of borehole resin production.

The economic cost of borehole tapping for its use of the forest resource is partly gauged by any effects it may have on tree growth or mortality. Logically, borehole tapping or any kind of exudate extraction is expected to cause some reduction in growth or vigor of the tree, insofar as this represents competition for

its carbohydrate reserves. However, the loss might be so small as to be inconsequential, or undetectable, since there is wide variation in the genetic predisposition to allocate nutrients between growth and defensive functions (Lorio, 1986). An objective for this project was to measure the effect of borehole tapping on tree growth rates.

The resource cost of borehole tapping is also partly determined by the length of time used, and the production period in relation to the overall forest rotation length. The rate of resin flow over time represents the marginal physical productivity and the incremental product recovery. Following from standard economic theory, the optimal duration for resin production occurs at the point when marginal costs equal marginal benefits. To evaluate alternative production schedules and to validate the systems model of borehole resin production, an objective for this research was to experimentally measure resin flow rates over time.

Borehole tapping causes physiological stress in the pine tree, as does any form of injury. An appropriate level of stress is necessary to activate the tree's defense response in order to obtain good resin yields, but excessive stress may result in undesirable effects, such as defoliation or insect attack, and ultimately reduce resin yields. A task for management of the borehole production system is to optimize tree stress levels through control of treatment intensities in relation to resource qualities and strategic management objectives.

Two alternative scenarios are envisioned for operation of a commercial borehole production system. One scenario involves intensively tapping trees for a relatively brief period immediately before they are harvested, with the objective of obtaining the highest possible yields in the shortest possible time. Since the trees are to be cut soon anyway, there is little concern for possible negative impacts on

tree health arising from chemical injury or insect attack, but there is a highly time-dependent opportunity cost. A second approach is to conservatively tap trees for an extended period, perhaps several years, with multiple treatments, to maximize long-term yields and forest resource utilization, and simultaneously minimize potential side effects. A specific objective for research was to measure production during a second consecutive year of borehole tapping.

High labor productivity and utilization is a key advantage of the borehole resin production system over conventional systems, and is essential to its commercial success and proliferation. A research objective was to evaluate new equipment for mechanized borehole tapping operations, including a semi-automated hydraulic-powered drilling machine and a specially manufactured spout-bag resin collection apparatus. Specific objectives were to evaluate clustered borehole configurations associated with mechanized systems for their effect on yields, and to assess the appropriateness of new systems by comparison of overall labor productivity of mechanized vs. non-mechanized systems.

A CONCEPTUAL MODEL OF THE BOREHOLE RESIN PRODUCTION SYSTEM

The purpose of this conceptual model is to provide a framework for understanding the fundamental factors affecting productivity of the pine oleoresin borehole tapping system, and for predicting yields in response to tapping treatments, over time and on a seasonal basis, for a range of tree sizes. The borehole production system is conceptualized as a closed-channel hydraulic system with storage of preformed oleoresin in capillary vessels, mass flow to the container through openings in the resin canal network, and inputs of newly synthesized materials from secretory cells, as depicted in Figure 3.1.

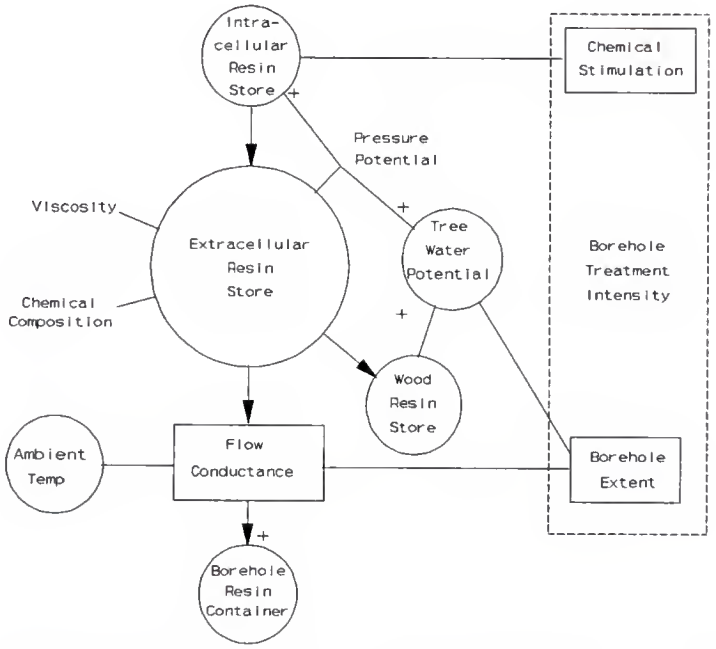

Figure 3,1. Schematic representation of borehole resin production system.

The borehole tapping system may be generally described in terms of 3 basic features: capacity, conductance, and pressure potential. The capacitance of resin available to borehole tapping is a function of tree stem volume, preformed resin density, and resin secretion rates. Density of preformed oleoresin stored within the tree's resin duct network is determined by the diameter, length, and density of ducts. Flow conductance from the extracellular resin store is affected by the extent of borehole wounding treatments and chemical composition and viscosity of the oleoresin itself. Pressure potentials driving resin flow arise from the mechanical elastic properties of the resin canal epithelium, xylem tissue turgor, and the vapor pressure of the collection container. An osmotic chemical potential exists between the resin secretory cells and the extracellular resin store, and is affected by CEPA chemical stimulation treatments.

Borehole wounds in the pine tree sever both radial and longitudinal resin ducts which form a network of drainage pathways, with directly and indirectly tapped ducts, as shown in Figure 3.2. Resin ducts directly intersected by boreholes have greater flow magnitude than those indirectly tapped by virtue of their shorter path length. Flow conductance of the resin ducts is a function of number of ducts sectioned, duct size (diameter and length), pattern of radial and longitudinal duct interconnections, and oleoresin physico-chemical properties, such as monoterpene content, viscosity, and crystallization rate.

Fundamental Laws Governing Resin System Behavior

Oleoresin flow was described by Poiseuille's law as expressed in equation 1, where the first term represents the pressure gradient driving flow along the duct, and the second term represents frictional resistance to flow within ducts.

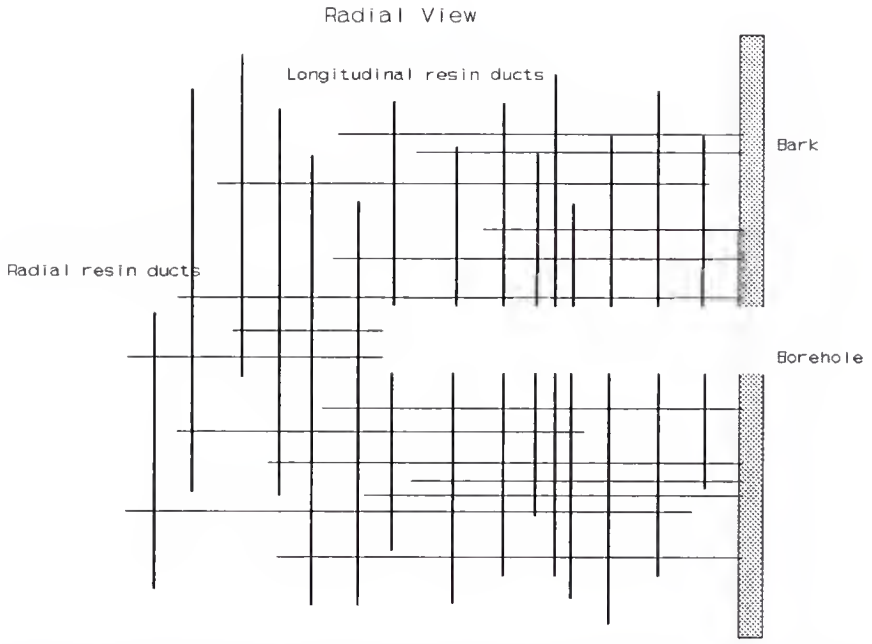

Figure 3,2. Flow pathways to a borehole wound in the resin duct network.

$$\gamma = \frac{\Delta P}{\Delta l} \times \frac{r^4}{8\eta} \qquad (1)$$

where γ *is flow rate ,*
ΔP *is pressure difference,*
Δl *is vessel length,*
r *is vessel radius,*
η *is viscosity.*

This model explained 75 percent of the variation in oleoresin flow rates for conventionally tapped slash pines (Schopmeyer et al., 1954). The opening diameter of resin ducts strongly affects the potential velocity of viscous flow, with the result that a few large-diameter ducts may dominate flow in a network of parallel pathways (Siau, 1971; Erikson, 1938). The velocity profile of a viscous fluid follows a parabaloid function of distance from the capillary wall, giving rise to the fourth power term in equation 1.

Pressure potential (P in eq. 1) is the driving force behind resin flow, and is a function of the difference in hydrostatic pressure between the resin duct system

and the external environment of the borehole wound and collection device. The potential energy stored in the pressurized fluid oleoresin is controlled by the mechanical elasticity of the resin ducts and the active chemical transport of secretion by the resin duct epithelial cells. The hypothesized general relationship governing oleoresin potential in the storage compartment is indicated in Figure 3.3, where pressure rises linearly with increased volume above a certain "rest volume" (V_R), which corresponds to the capillary pressure (P_A) in its discharged state.

The pressure required to express a viscous fluid from a capillary is an inverse function of capillary diameter (Siau, 1971). The relationship is described by equation 2, where the left hand side is the pressure potential difference (psi) between the capillary and the environment, R is the vessel radius (micrometers), and A is a constant representing the specific capillary adhesion of the material (A = 90 for Hg).

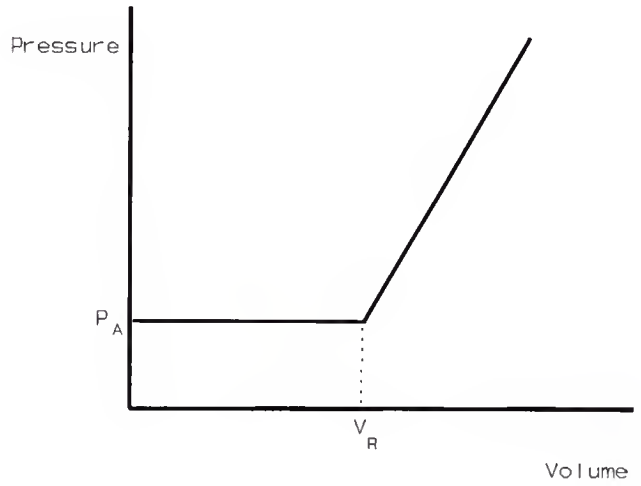

Figure 3,3--Relationship between oleoresin pressure and volume in the oleoresin duct store.

$$P_1 - P_0 = \frac{A}{R} \qquad (2)$$

The consequence of this relationship is that only a portion of resin ducts contribute to flow at a given pressure potential. Changes in the pressure potential correspond to a change in the minimum diameter of ducts which can be expressed, as described by the curve in Figure 3.4.

Pressure potential differences may be influenced by borehole tapping techniques. Tightly sealed borehole collection containers essentially act as closed-end manometers, with gas pressure in the headspace rising as a function of resin volume, according to the relationship depicted in Figure 3.5, and described in equation 3, where the change in pressure (in atmospheres) represents the gas compression ratio, C is the capacity of the container (2000 ml), Y is resin yield (gm), and D is resin density (1.065 gm/ml).

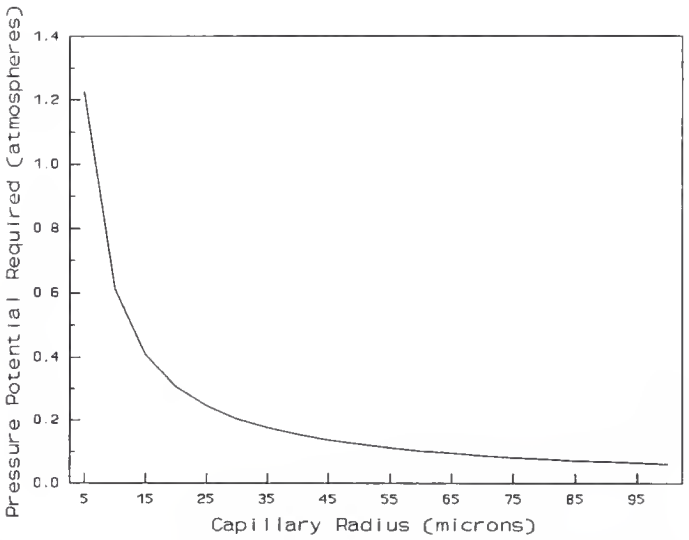

Figure 3,4. Pressure required to express a viscous fluid (Hg) from a capillary as a function of capillary diameter.

$$\Delta P = \frac{C}{C - \frac{Y}{D}} \qquad (3)$$

This functional relationship is based upon Boyle's law for an ideal gas, where the product of pressure and volume is a constant. An increase in the container pressure corresponds to a decrease in the net system pressure potential. It is expected that the ultimate yield under these conditions is indicative of the inherent pressure potential of the tree.

The pressure potential of the oleoresin store may also vary due to changes in the turgor pressure of ambient woody tissue surrounding the resin ducts (Lorio and Hodges, 1968; Vite, 1961). Water is transported in the xylem under negative pressures exerted by evapotranspiration (ET) in the canopy, with diurnal and

seasonal variation in oleoresin system pressures accompanying changes in xylem water potentials (Zimmerman, 1983). Interruption of the transpiration stream by borehole treatments is likely to cause cavitation in tissues above holes, but could result in increased pressures below holes due to separation from the negative potential source.

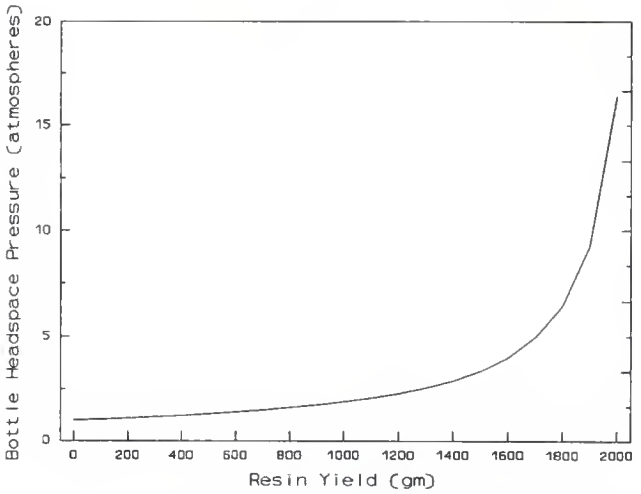

Figure 3,5. Gas pressure in sealed 2-liter borehole containers as a function of resin yield.

Xylem water potentials are normally lower in the interior portions of the stem due to general senescence processes, reflected by deposition of extractives and heartwood formation (Hillis, 1987). It is hypothesized that reduced oleoresin exudation pressure potentials will result in lower resin yields from boreholes which penetrate this region, and the incipient heartwood tissue may act as a sink for deposition of oleoresin (Figure 3.1).

A hypothesized model of resin flow over time is shown in Equation 4, where parameter B_1 represents capacitance and potential factors determining the cumulative final yield of resin, and parameter B_2, the time constant, represents resin flow conductance.

$$Y(t)=B_1(1-e^{-t\cdot B_2}) \qquad (4)$$

This model was fitted to data for resin yields over time. The negative exponential form of this flow rate function implies a fixed capacity flow source system (France

and Thornley, 1984), and is consistent with resin flow rates observed in conventional gum resin tapping (Harper and Wyman, 1934; McReynolds and Kossuth, 1984, 1985). It is also hypothesized that the sensitivity of the borehole resin system to environmental perturbations follows this same functional relationship, as was shown for the effect of weather conditions on conventional open-face resin production (Harper and Wyman, 1936).

A Basal Area Representation of Oleoresin Storage and Flow

As a consequence of the arrangement of radial resin ducts, the effective region of tissue tapped by borehole wounds is bounded by a pie-shaped sector of the tree stem subtended by the horizontal extent of the hole, as shown in Figure 3.6.

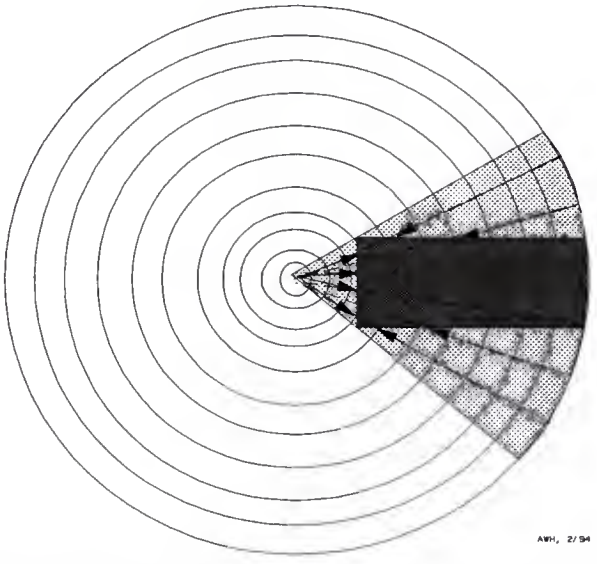

Figure 3,6. Resin flow in the borehole production system from radial sector area.

This sector is indirectly drained above and below the hole due to the dense interconnection of radial and longitudinal resin ducts.

An area-based representation of tree resin store capacity was chosen because of its generality for tree growth processes, and the availability of forest yield models developed in terms of tree basal area per unit land area (e.g. Bailey et al., 1982, Pienaar et al., 1990). A volume-based representation was not possible because the length of longitudinal resin ducts is not known precisely.

The stem cross-sectional area was divided into three compartments as depicted schematically in Figure 3.7 for three types of borehole configurations.

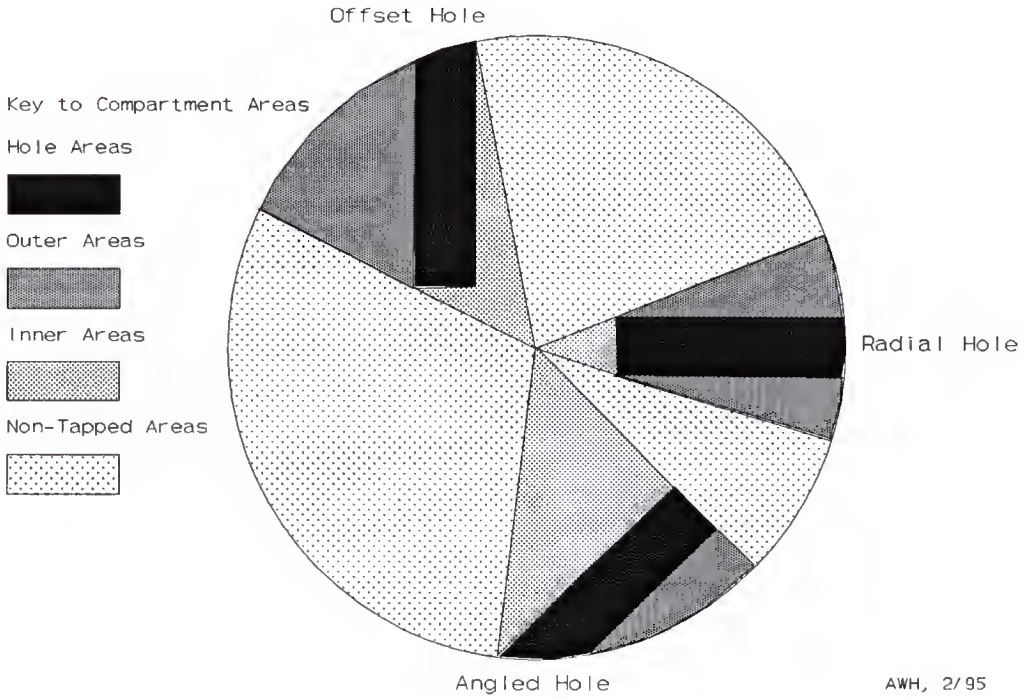

Figure 3,7. Resin system compartment areas for borehole tapping.

The area of the borehole itself is the "hole" compartment. An "outer" compartment area of the stem is a sector extending from the radius projected from the tip of the hole, to the lateral face of the hole, while an "inner" compartment occupies the residual sector area between radial lines projected to extreme corners of the hole profile. Comparison of yields per unit area of the respective compartments will allow a gross estimation of their relative contribution to the total flow. For all three hole configurations, the sector angle subtended is sensitive to the depth of the hole, especially as holes approach the center of the stem.

Resin flows centripetally from the outer compartment, and centrifugally from the inner compartment. This pattern differs fundamentally from that occurring in nature and in the conventional open-face production system where resin flows only

from the radial ducts in a centrifugal direction. The fact that resin flow in the centripetal direction occurs along a decreasing water potential gradient in the tree's stem is probably a key factor for productivity of the borehole tapping system.

Management Related System Factors and Experimental Treatments

To validate, calibrate, and apply the conceptual model of the borehole oleoresin production system to the operating management of a borehole tapping enterprise, a series of experiments were conducted that manipulated the fundamental system factors. Experimental factors available to test the conceptual model of the borehole resin production system are summarized in Table 3.1.

Hole dimensions and orientations are matters for both system design and day-to-day management of borehole tapping, and generally, these treatment factors affect both capacitance and pressure potential system factors, but in opposing directions. The cross sectional area of longitudinal resin ducts directly tapped is proportional to the depth, diameter, and number of boreholes, while orientation of the hole axis, both horizontally and vertically, affects the number of radial ducts sectioned. Horizontal and vertical separation of adjacent holes affects the number of second-order pathways tapped. Spacing among holes affects the local tissue pressure potentials, but effects may not be directly additive due to overlapping zones of influence. Following from economic principles, it is predicted that there exists an optimum level of borehole extent where the rate of increased yield due to greater capacity is equal to the rate of decrease due to reduced pressure potential.

Table 3.1. Summary of resin system management domains, model factors and experimental variables.

Management Domain	Experimental Variables	System Model Factors
Hole extent and placement treatment factors	Hole diameter	Capacitance, Potential
	Hole depth	
	Hole vertical orientation	
	Hole horizontal orientation	
	Number of holes per tree	
	Hole vertical separation	
	Hole horizontal separation	
Chemical/biological treatment factors	CEPA level	Potential, capacitance
	Sulfuric acid (H_2SO_4) level	Conductance, Capacitance
	Fungal culture extract	Potential, capacitance
Borehole technology factors	Borehole machining quality	Conductance
	Sprayer type	Capacitance
	Collection container	Potential
Resource selection factors	Species, variety	Conductance, Capacitance, Potential
	Tree size	Capacitance
	Physiographic region	Capacitance, potential
	Site quality	Capacitance, potential
Production scheduling	Seasonality of treatment	Conductance, Potential

Chemical and biological treatments of borehole wounds affect capacity, conductance, and pressure potential factors. Chemical treatment with CEPA stimulates resin synthesis, which simultaneously increases production capacity and maintains pressure potentials in the resin duct system. Sulfuric acid treatment acts to increase conductance by destroying cells which surround the openings of severed resin ducts, and delay the onset of duct occlusion (Ostrum et al., 1958).

Biological treatments with extracts of fungal cultures have been shown to increase the flow of oleoresin from wounds within 2 days of wounding (Popp et al., 1991), and decrease sapwood conductance after colonized by the fungi (Parmeter et al., 1992), so it could conceivably enhance or reduce borehole resin yields.

The borehole treatments can be understood in terms of the intensity of their effects on the fundamental system factors. In general, larger hole extent and higher chemical treatment concentrations or molar volumes are expected to inflict higher intensity effects on the resin system.

Other factors pertinent to management of the borehole resin production system which are reflected in the system model are technological, resource quality, and seasonal factors. The borehole container type affects pressure potentials, and is a discriminating factor between capacitance and potential. Tree size determines the overall capacity of the system. Site quality may have complex effects on system capacitance and potential due to alterations in the balance between growth and differentiation. Time of year for borehole treatment is expected to similarly affect system behavior through capacitance and potential, with seasonal variation in oleoresin exudation pressure, and additionally through the effect of temperature on resin conductance.

METHODS FOR BOREHOLE TAPPING EXPERIMENTS

Research Sites and Plots

Borehole-tapping studies with Slash pine were conducted between 1991 and 1994 at eight sites in Florida and Georgia (USA), which are summarized in Table 4.1. Resin yields were measured for 668 trees and 1575 boreholes, including 1337 individual borehole measurements in 528 trees. Trees were 25 to 40 years old, with diameters at breast height (dbh) ranging from 18 to 41 cm (7 to 16 inches). Site quality indices for slash pine ranged from 24.4 to 28.0 m height at 25 yrs.

Table 4.1. Sites and plots for borehole tapping experiments, slash pine, 1991-94.

Site Location	Site Index (meters ht. at 25 yrs.)	Average Tree DBH (cm)	Date Began	Period (Days)	Number Trees	Number Holes
Gainesville, FL	24.4	27.2	21-Apr-94	178	20	60
		26.4	23-Jun-94	158	44	144
		27.2	21-Aug-94	133	15	45
		26.4	8-Sep-94	115	20	70
Waldo, FL	27.4	31.5	4-Jun-92	128	27	102
Hosford, FL	na	31.2	21-Jul-92	117	48	124
		31.5	4-May-93	199	51	120
Homerville, GA	na	na	17-Jul-91	162	15	23
McRae, GA	25.6	24.1	7-May-91	162	60	84
		28.4	1-Jun-92	137	167	459
		na	24-May-93	198	10	20
		30.5	2-Aug-94	99	21	40
Soperton, GA	28.0	24.4	7-May-91	162	20	24
Eastman, GA	25.6	na	24-May-93	199	10	20
Waycross, GA	27.4	na	1-Jul-93	172	140	240
Total					668	1,575

Resin production was measured for periods of 99 to 199 days between April and December. A small number of Longleaf pines (*Pinus palustrus*) were incidentally tested for borehole resin production during these experiments, and small numbers of tropical pines (*P. caribean, P. oocarpa*) were tested in Venezuela. A factorial experiment with Maritime pine (*Pinus pinaster*) was conducted in the Landes region of southwestern France during September 1994, in a 50 year-old stand with 110 trees and 297 total boreholes.

Borehole Treatment Procedures

Borehole tapping experiments followed three operational steps: boring holes in the tree at the prescribed position, depth, and orientation; applying a chemical spray treatment; installing the resin collection apparatus. Each of these steps involved technology innovations, for development and testing of a mechanized tapping system, as described in the final section.

Hole boring was done with a double-spur, double twist self-feeding drill bit 2.54 cm in diameter (1.0 inch) at approximately 1000 rpm. This type of drill bit has a very clean cutting action to avoid tearing wood fibers, and a self-feeding screw point that controls the drill feed rate. The drill was powered by a 2.2 kw chainsaw engine and drilling attachment (Atom Industries, Sydney, Australia). Holes were drilled to a depth of 5.1 to 17.8 cm, measured from the bark-xylem interface.

Chemical spray treatment was done immediately after boring holes to get good spray contact and uptake before the quickly-exuding resin covered and sealed the wood surface. Spraying was done with either a naval stores spray bottle, a 11.4 liter pressurized sprayer, or hand-held pump sprayer. The naval stores spray bottle (Evans) is a finely atomizing aspirated sprayer, which is used throughout the world in gum resin operations. The pressurized sprayer (2.8 kg/cm^2) was a garden-

type spray tank which produced a similarly fine spray particle size. The common household-type hand pump sprayer produced a somewhat coarser cone-shaped spray pattern, but delivered a constant dose by virtue of its fixed volume displacement. Chemical solutions were mixed in volumetric concentrations of 0 percent to 15 percent (ai) of 2-chloroethyl-phosphonic acid (CEPA, Rhone-Poulenc Co.) and 0 to 25 percent sulfuric acid (H_2SO_4). Chemical volumes of 1 to 2 ml were applied to each hole, resulting in dosages of 0 to .28 ml a.i. of CEPA.

Sterilized extracts of the Blue Stain fungus (*Ophiostoma* spp) were applied as an additional biological treatment in experiments at Gainesville FL in 1994. The extract was prepared from a laboratory strain of *Ophiostoma* cultured on an agar medium, by homogenizing, then autoclaving to kill the microorganisms, and filtering through cheesecloth to remove large particles of mycelia. The sterilized extract was mixed with a stock solution of CEPA and H_2SO_4 to give a concentration of 2.1×10^7 spores ml^{-1}, in order to apply a target population of spores 1.05×10^6 cm^{-2} hole cross sectional area, following from Popp et al. (1991).

Containers used for resin collection from boreholes were either 2-liter PET bottles or a spout-bag apparatus. For the first three-year's experiments (1991-93), recycled 2-liter PET beverage bottles were attached for resin collection by screwing into the borehole with the bottle's existing cap threads and left in place for the duration of the season. A spout-bag collection device was a key technological innovation introduced in the last year of the project (1994), which enabled measurement of resin flow rates over time. Two types of spouts used were a general purpose hose adapter (PVC 3/4" NPT), and a specially manufactured injection-molded HDPE device (patent-pending, Navstoc, Inc., Boca Raton, FL). Both types of spouts were installed by gently hammering with a small mallet or pushing with the palm of the hand to achieve a compression fitting in the hole. Individual

plastic bags made of HDPE or LDPE were attached to spouts on each borehole, and were repeatedly replaced to collect resin flow for periods of 1 to 2 months. The spout-bag and PET bottle collection devices are shown in Figures 4.1 and 4.2.

The different treatments and their levels used in all experiments are summarized in Table 4.2. A total of 11 different experimental variables were manipulated with 2 to 7 discrete levels of each treatment variable, however, only 2 or 3 levels of treatment variables were manipulated simultaneously in a given experiment.

Table 4.2. Treatment variables and levels used for borehole tapping experiments, 1991-94.

Variable	Treatment Levels
Hole depth	8.9, 10.2, 11.4, 14.0, 15.2, 17.8 cm
Hole vertical orientation	0 or 45 deg. from transverse horizontal plane
Hole horizontal orientation	0 to 25, 30 or 45 deg. from radial plane
Clustered hole horizontal separation	4.8, 7.6, 9.7, 10.2, 15.2 cm
Clustered hole vertical separation	0, 4.78 cm
Number of holes per tree	1, 2, 3, 4, or 5 holes
CEPA dose (ml/hole)	0.0, 0.02, 0.04, 0.08, 0.12, 0.15, 0.18, 0.28 ml/hole
Sulfuric acid (H_2SO_4) dose	0.0, 0.2, 0.3 ml/hole
Fungal culture extract of *Ophiostoma*	yes, no
Collection container	2 liter PET bottle, PE spout/bag apparatus
Month of treatment/installation	April, May, June, July, August, September

Figure 4,1. PET bottle borehole resin collection devices installed in tree.

Figure 4,2. Spout-bag collection apparatus used in 1994 experiments with clustered borehole pattern.

Yield Measurements and Tree Observations

Net resin yields were measured by weighing resin containers for each borehole with a spring scale to the nearest 5 g or 25 g. Cumulative seasonal yields were taken for all trees at 99 to 199 days since drilling. Intermediate yields were measured for 79 trees at Gainesville FL in 1994, at 7, 25, 50 and 84 to 112 days following borehole treatment.

Tapped trees were observed for signs of physiological stress, including discoloration or loss of leaves, attacks by Black Turpentine beetles (*Dendroctonus terebrans*), presence of other wood and bark boring beetles (*Ips* spp.), and mortality. Loss and discoloration (browning) of the leaves, which occurred in some trees as a result of CEPA treatment, was estimated as a percentage of the canopy affected. Attacks by Black Turpentine Beetles (BTB) were noted on a weekly basis by counting the number of fresh and old pitch tubes present on the lower tree bole. During periods of massive BTB attacks, trees were sprayed with Lindane. A composite index of tree stress was developed by combining the measures for individual stressors of canopy defoliation, and incidence of beetle attacks.

Weather data for the period of 1994 experiments in Gainesville FL were obtained from the nearby National Weather Service station, by retrieval from the AWARDS database maintained at the University of Florida. Daily records were compiled for photosynthetically active radiation (PAR), average, maximum and minimum temperatures, rainfall, and humidity. Effects of daily and cumulative weather fluxes on resin flow rates in the four seasonal plots were tested by statistical analysis.

Design of Borehole Tapping Experiments

Borehole tapping experiments included simple yield tests with no treatment variation, controlled studies of a single treatment variable, and intensive studies in which multiple treatment factors were systematically varied. The simple field tests at the Soperton (1991), McRae (1991), and Waycross (1993) sites involved 2 to 5 uniformly treated boreholes installed in each tree at evenly spaced circumferential positions. Controlled experiments with paired treatments in each tree were done at McRae site (1994) to measure the effect of collection container types (2-liter PET bottles vs. spout-bags), and at the Hosford, McRae and Eastman sites (1993) to test large vs. regular diameter boreholes. Intensive studies with factorial experimental designs were conducted at Gainesville FL in 1994, at McRae GA and Waldo FL in 1992, and at Hosford FL in 1992-93.

Investigations at Austin Cary Forest near Gainesville (1994) were designed as a replicated series of plots with fractional factorial experimental arrays and within-subject experimental controls. Treatment levels were blocked to obtain the greatest possible number of within-subject (tree) experimental contrasts, and were roughly balanced in numbers. These procedures were taken in order to increase statistical power to detect relatively small treatment effects against the large background variability between trees. A total of 318 boreholes were made in 99 trees, with 3 or 4 boreholes each. Four separate experimental plots were established in April, June, August, and September, with 15 to 44 trees each, to measure seasonal effects on borehole tapping yields (Table 4.1). In the April, June, and September plots, the fractional factorial experimental design tested the effect of hole number, depth, vertical orientation, horizontal spacing, and CEPA chemical spray treatments. Groups of 2 or 3 clustered holes were installed in various

combinations of spacing and depth as shown in Figure 4.3. Trees in these plots also included a within-subject control in the form of a single borehole receiving uniform treatment on the opposite side of the tree. Hole number, depth, orientation and spacing treatments were administered at two levels representing "high" and "low" values, while CEPA spray treatments were made at three levels representing "high", "low" and "medium" values. These five factors were arrayed by cyclical permutation in a total of 36 different combinations, as shown in Table 4.3.

Experimental treatments at Gainesville (1994) were also stratified for balanced random assignment within three tree size classes as a control for resource quality (tree size) effects. This form of experimental design was used to develop process settings that maintain robust control of yield responses in the face of environmental variation.

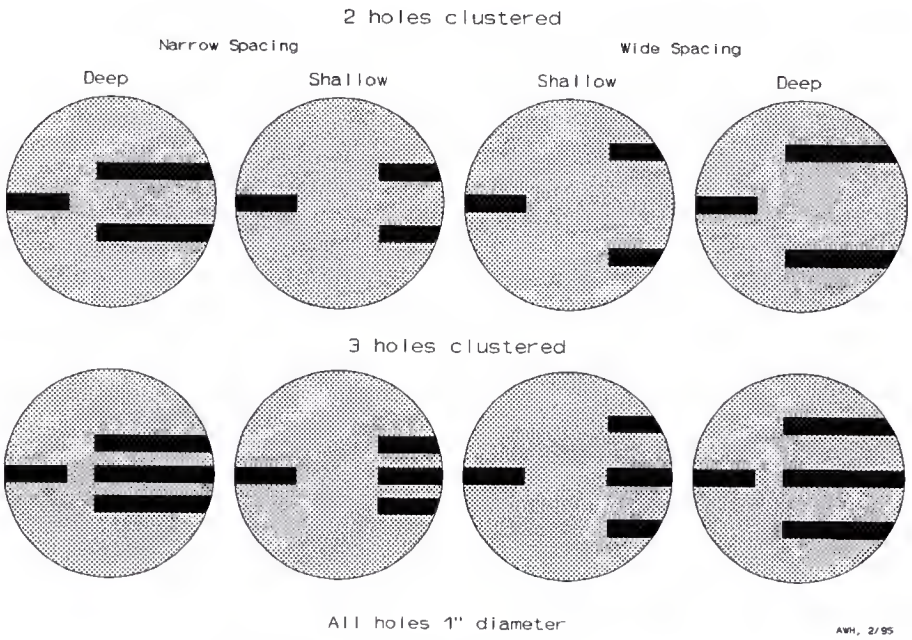

Figure 4,3. Hole treatment patterns for clustered experimental holes at narrow and wide spacings, and deep (17.8 cm) or shallow (8.9 cm) depths, with a single control hole (8.9 cm deep) on opposite side.

Table 4.3. Design matrix for fractional factorial borehole tapping experiment, Gainesville FL, 1994, June plot. Numbers indicate treatment levels.

Tree	Tree Size Class	Number of Holes	Horizontal Seperation between Holes	Verticel Angle of Holes	CEPA level	Depth of Hole
1	1	2	1	0	1	1
2	2	3	1	0	1	1
3	3	2	2	0	1	1
4	1	3	2	0	1	1
5	2	2	1	1	1	1
6	3	3	1	1	1	1
7	1	2	2	1	1	1
8	2	3	2	1	1	1
9	3	2	1	0	2	1
10	1	3	1	0	2	1
11	2	2	2	0	2	1
12	3	3	2	0	2	1
13	1	2	1	1	2	1
14	2	3	1	0	2	1
15	3	2	2	1	2	1
16	1	3	2	1	2	1
17	2	2	1	0	3	1
18	3	3	1	0	3	1
19	1	2	2	0	3	1
20	2	3	2	0	3	1
21	3	2	1	1	3	1
22	1	3	1	0	3	1
23	2	2	2	1	3	1
24	3	3	2	1	3	1
25	1	2	1	0	1	2
26	2	2	2	1	1	2
27	3	2	1	1	3	2
28	1	2	2	1	1	2
29	2	2	1	0	2	2
30	3	2	2	0	2	2
31	1	2	1	1	2	2
32	2	2	2	1	2	2
33	3	2	1	0	3	2
34	1	2	2	0	1	2
35	2	2	1	1	3	2
36	3	2	2	1	3	2

Compartment Model Area Calculations

The cross-sectional areas of the tree stem affected by borehole-tapping treatments were calculated for the three-compartment model illustrated in Figure 3.7, using the parameters shown in Figure 4.4.

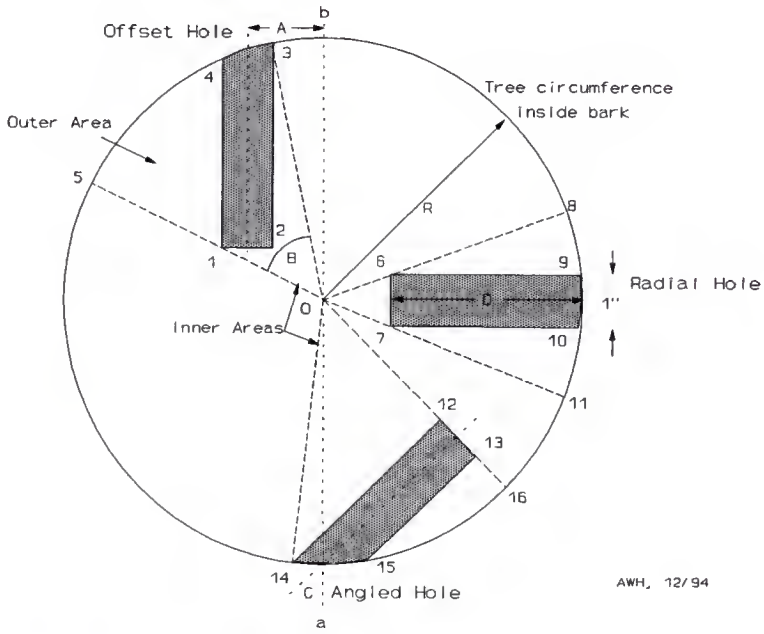

Figure 4,4. Area calculations for compartment model.

Formulae for calculating areas (cm^2) were developed for the three basic hole types--radial, angled, and offset--based upon a Cartesian coordinate system for the corner points of each hole, with the center of the tree as the origin (O) and a radial axis through or parallel to the hole (line ab). The tree radius inside bark at a height of 6 inches (R) was estimated from DBH measurements using a formula from Bailey (1994) which described stem taper and bark thickness as a function of height above ground. Sector areas subtended by rays projected to the extreme corner points of holes were calculated from trigonometric formulae (areas O-3-5-O, O-8-11-O, O-16-14-O), using the interior angle of the sector (B). The cross sectional area of the hole itself was approximated as a polygon (areas 1-2-3-4, 6-7-9-10-6,

12-13-15-14-12). The inner compartment areas were calculated either as a triangle (areas O-6-7-O, O-12-14-O) or a concave polygon (area O-1-2-3-O). The outer compartments (areas 1-4-5-1, 13-15-16-13, 6-8-9-6 and 7-10-11-7) were derived as the residual of the total sector area. Compartment areas for each hole were divided into the hole yield to derive intensive measures of yields per unit area. Areas and yields were also summed for each tree to analyze area-specific yields on a whole tree basis. In the case of downward-oriented holes, the horizontal profile projected by the hole was used to calculate its compartment areas, and for cases in which the hole reached the center of the tree stem, sector angles and areas were not calculated.

Increment Core Analyses for Borehole-Tapped Trees

To test the effect of borehole resin production on tree growth, increment cores were taken and measured in the field for groups of 41 tapped trees and 25 neighboring untapped trees on two different sites, at McRae GA, in February, 1994. The tapped trees had been tapped for 120 days from June to October in 1992. Tapped and untapped trees selected for core sampling were matched with respect to tree size on both sites (avg. DBH 24.6 vs. 25.4 cm). Increment cores were taken at breast height. The width of rings on each core was measured (to nearest mm) for the last 2 years and 5 years, providing a measure of radial growth during the 3 year period before tapping and the 1.8 year period since tapping began. In particular, the increment cores were read from the outermost latewood layer (cambium-xylem interface), to the second and fifth latewood-earlywood margin. These measurements feature a within-subject experimental control, by comparison of growth rates before and after the tapping treatment in each tree.

Increment cores were taken from all trees at the Gainesville FL, 1994 site for measurement of radial growth rates, sapwood thickness, and inside bark radii at stump height. Wood cores (0.51 x 20 cm) were sampled from positions above and between opposing borehole clusters (Figure 4.5), at a level slightly above the boreholes, approximately 15 cm above ground.

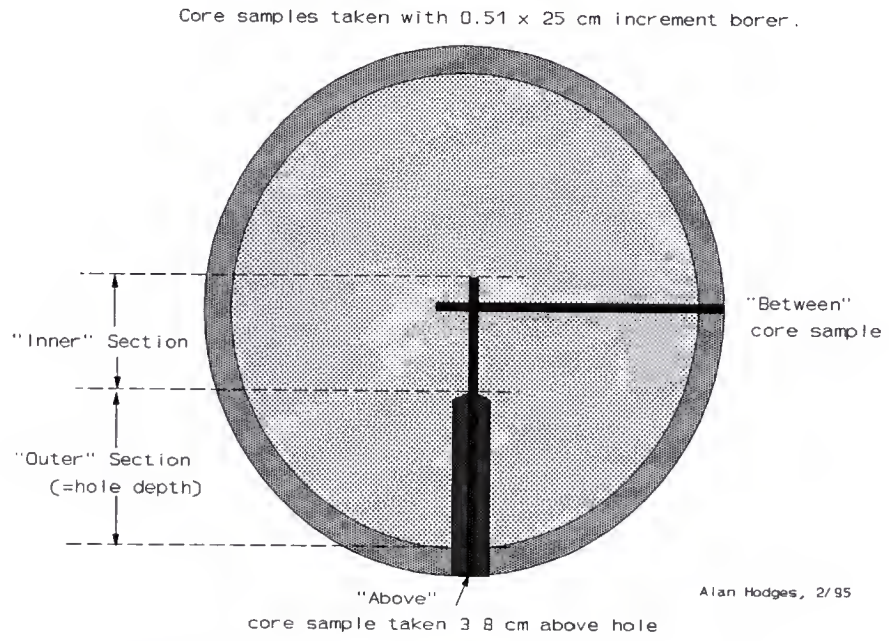

Figure 4,5. Increment core sampling plan, Gainesville FL, 1994.

Cores taken from the "between" position (Figure 4.5) were examined and measured with the aid of a dissecting microscope and 0.5 mm ruler. Tree growth was measured by width of the last 5 year's radial increment on the cores. Resin-saturated wood noted on the inner part of many cores was taken as evidence of premature heartwood formation, or tapping-induced resinosis. In other cores, a zone of incipient heartwood was identified by its characteristic discoloration (Hillis, 1987). The thickness of sapwood was measured from the xylem-bark interface to this zone of discolored or resin-saturated wood (if any), and tree stem sapwood areas at borehole level were calculated.

Wood densities in inner and outer portions of radial increment cores were measured for 18 trees in the April plot, by dividing cores into an outer 114 mm section, representing wood directly above boreholes (11.4 cm deep), and an inner section of the remaining length. Cores were weighed (mg) before and after drying in a forced air oven for 24 h, and green and dry densities were then calculated on the basis of the original core section volumes.

Extractive analysis of increment core wood samples was done for a small group of trees (n=4), to measure monoterpene densities after borehole tapping. Increment cores were kept frozen to prevent loss of volatile terpenes, then were extracted in 15 ml pentane, and a 1 ml sample with a 160 ppm para-cymene internal standard were injected into a Hewlett-Packard gas chromatograph (HP5890) and integrator (HP3394A). The original volume and dry weights of the cores were used to calculate monoterpene densities on a whole-tissue basis.

Physico-Chemical Analysis of Oleoresin Produced by Borehole Tapping

Resin from borehole tapping was analyzed for characterization of physical and chemical properties possibly affecting system behavior. Composite samples from the McRae (1993) plot were prepared and separately analyzed for 7 groups of 9 to 10 trees receiving each chemical treatment combination of H_2SO_4 (0, 25%) and CEPA (0, 5, 10, 15% relative concentration). Physical properties analyzed included monoterpene and resin acid composition, crystallization, and boiling and softening points. A rosin crystallization test was done with solid rosin dissolved in acetone, and timed for appearance of crystals. Analysis of resin acid composition was done by capillary-gas chromatography, with flame ionization and a methyl ester internal standard (ASTM standard D 3008). Samples from 67 trees in the

Gainesville FL (1994) experiments were subjected to laboratory analysis to measure viscosity (#2 rotary viscometer @ 50 deg C) and softening points.

Data Analysis Procedures

Resin yield data for all borehole tapping experiments were combined to provide increased statistical power for analysis of treatment and resource effects, and support of systems analysis and modeling. Data were recorded, checked, compiled, summarized and plotted in *Lotus 1-2-3* worksheets (ver. 3.4, Lotus Dev. Corp, Boston, MA). Simple statistical tests were performed with @*STAT*, an add-in software package for *Lotus 1-2-3*. *Freelance Graphics* (Lotus Dev.Corp) and *StatMost* (DataMost Corp.) software packages were used for plotting data.

Data were further analyzed with statistical model testing and fitting procedures available from the *SAS System* (SAS Institute, 1988). The General Linear Models (GLM) procedure was used to test all main and interactive treatment effects, and for performing both univariate and multivariate analysis of variance for within-subjects, repeated-measures experimental designs. The GLM procedure is convenient for handling both continuous and discrete (class) independent variables. Differences between treatment means were evaluated with Tukey's test, a conservative multiple comparison procedure that controls the mean experimentwise error rate. Dependent variables specified in GLM analyses represented cumulative hole yields (gm) or tree yields (gm), and derived yield measures expressed on the basis of time or cross-sectional area tapped (gm/day or gm/cm^2).

Response surface analysis (SAS RSREG procedure) was used to determine the optimal treatment conditions for maximizing yields (SAS Institute, 1988; Box et al., 1978). The RSREG procedure finds the best-fitting linear model with an algorithm that rotates the model vector through the experimental design matrix. A

related "ridge analysis" procedure was used to find the set of treatment level values corresponding to the point of predicted maximum yield on the response surface (Draper, 1963). Inspection of the matrix of eigenvalues indicated whether the stationary point was a local maximum or a saddle point.

A least-squares fitting procedure for non-linear models (SAS NLIN procedure) was used to estimate the parameters for negative exponential models of cumulative resin flow over time, and area-specific resin yields as a function of tapping intensity. The procedure required specification of a model regression equation, initial parameter values, and derivatives of the model with respect to each parameter. An iterative algorithm (Marquardt method) was used to find the best-fitting model parameters by regressing the residual sum-of-squares (error) onto the partial derivatives of the model with respect to the parameters until the estimates converged, typically within 5 to 10 steps.

BOREHOLE-TAPPING EXPERIMENT RESIN YIELD RESULTS

Effects of Resource Quality

Species

Borehole resin yields were highly species-dependent. Seasonal yields per borehole for slash pine (*P. elliotti*) averaged 657 g (SE = 11 g). Yields were an order of magnitude lower for most other species tested, including longleaf pine (*P. palustrus*) in the southeastern US, Maritime pine (*P. pinaster*) in Southwestern France, and Caribean pine (*P. caribea* var hondurensis) in Venezuela, in spite of similarly intensive tapping treatments (Table 5.1). Only *Pinus oocarpa*, a Central American species showed any promise for borehole production, with yields averaging 200 g (P. deLarosiere, pers. com).

Table 5.1. Borehole resin yields by species, 1991-1994.

Species	Country	Average Borehole Yield (gm)	Number Boreholes
Slash pine (*P. elliotti*)	USA	657	1557
Longleaf pine (*P. palustrus*)	USA	86	20
Caribean pine (*P. caribea*)	Venezuela	40	20
P. oocarpa	Venezuela	200	20
Maritime pine (*P. pinaster*)	France	28	297

Resin yields were available for 528 slash pine trees with 1337 individual boreholes. A plot of the frequency and cumulative distribution of borehole resin yields is shown in Figure 5.1.

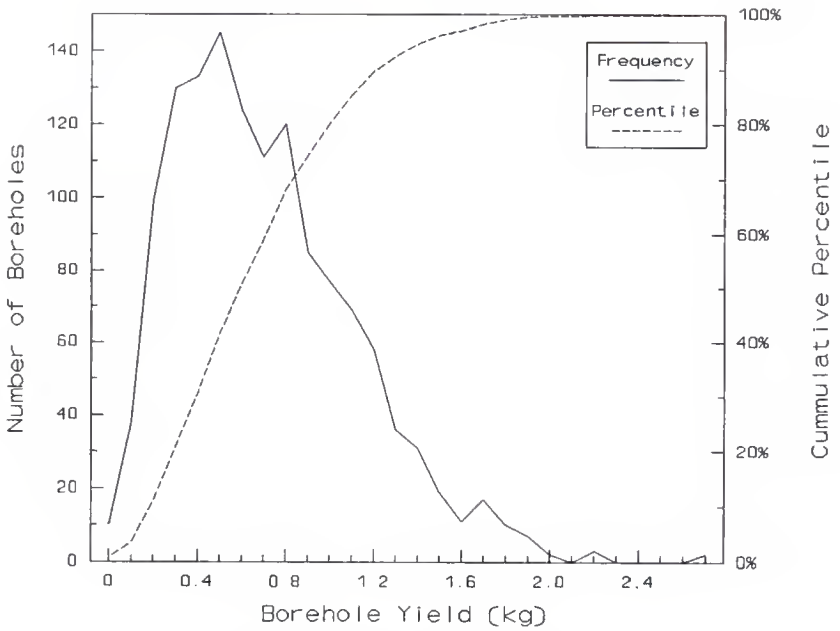

Figure 5,1. Distribution of borehole resin yields, slash pine, 1991-94. Represents 1337 boreholes.

Individual borehole yields ranged as high as 2100 g, with 20 percent producing more than 1 kg, and approximately 7 percent of boreholes produced less than 100 g. Seasonal yields per tree averaged 1,663 g (SE = 46 g), and ranged from zero to over 8 kg.

Sites

Yields for slash pine varied dramatically among the eight sites in Florida and Georgia, from over 1200 g to less than 500 g per borehole (Table 5.2). The very high yields at the McRae and Eastman GA sites represented a combination of good site quality, large trees, and high chemical treatment levels. Yields in the 1994 plot at McRae GA averaged nearly 2 kg per hole. Yields at the two sites in peninsular Florida (Gainesville and Waldo) were generally lower than for most other sites in Florida and Georgia. Yields per hole were lowest of all at the Soperton GA site (443 g), where the very high site quality (SI = 92) and the genetically improved (high

gum-yielding) slash pine stock resulted in rapid timber growth at the expense of resin production.

Table 5.2. Summary of borehole resin-tapping seasonal yields by site, slash pine, southeast US. 1991-1994. Means with different letter superscripts were significantly different ($p < .05$, Tukey's test)

Site	Number of Bore-Holes	Seasonal Yield (gm)		
		mean	SE	CV
Gainesville FL	318	497[bc]	20	72
Waldo FL	102	552[b]	32	58
Hosford FL	247	643[ab]	23	56
McRae GA	603	759[a]	17	55
Eastman GA	20	1233	129	47
Soperton GA	24	443[c]	66	73
Homerville GA	23	542	87	77
Waycross GA	240	903	na	na

Variability in borehole yields was comparable across sites, with coefficients of variation ranging from 44 to 77. Higher levels of variation were mostly associated with experimental manipulations rather than inherent site differences.

Tree Size

Tree stem volume was the most important single variable influencing borehole resin-tapping yields, both in terms of individual holes and whole trees. Yields for large and very large trees (greater than 27.9 cm) were significantly greater than small and medium trees, and average yields per hole for very large trees (over 33.0 cm DBH) were two thirds greater than for small trees (less than 22.9 cm), as shown in Table 5.3. On a whole tree basis, overall yields for larger trees were of course greater due to a higher number of holes. Tree yields on a unit hole area basis were greater for large and very large trees. Tree size also interacted with other treatment effects which significantly affected resin yields.

Table 5.3. Borehole resin-tapping seasonal yields by tree size, slash pine, 1991-1994.

Tree Size (cm DBH)	Number of Bore-Holes	Seasonal Yield (gm)		Tree Yield Per Unit Hole Area (gm/in^2)
		mean	SE	
small (less than 22.9)	125	527[a]	39	22.8[a]
medium (22.9 to 27.9)	376	551[a]	18	21.7[a]
large (27.9 to 33.0)	454	681[b]	18	25.4[b]
very large (greater than 33.0)	319	779[c]	25	25.9[b]

Means with different letter superscripts were significantly different ($p<.05$, Tukey's test).

Results for 1994 experiments at Gainesville FL, where numbers of holes were balanced across tree size classes, confirmed the strong effect of tree size and resin system capacity on resin yields. Large and very large trees produced yields nearly twice as great as small trees, on both individual borehole and whole tree bases (Table 5.3). Yields of larger trees were consistently greater across time, with significant differences appearing at one month after borehole treatment, as shown in Figure 5.2

Borehole Tapping Treatment Effects

Borehole Diameter and Depth

In general, significantly higher resin yields were obtained for large and deep holes, and holes drilled at angles displaced from the radial axis. The effect of hole diameter on yields was investigated with paired 3.49 cm (1.375 inch) and 2.54 cm (1.00 inch) holes on a total of 35 trees at the Hosford FL, McRae and Eastman GA sites in 1993. Yields for large diameter holes averaged 996 g compared to 822 g for the standard 2.5 cm hole (Table 5.4), a statistically significant difference ($p<0.05$) by a paired t-test. However, the 21 percent greater yields for larger holes

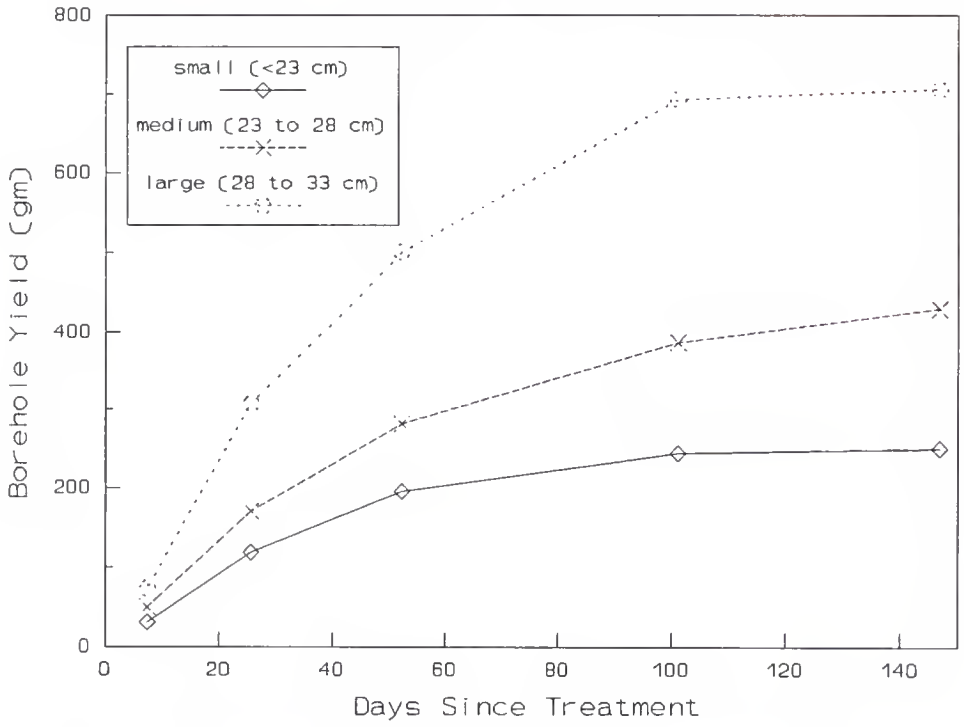

Figure 5,2. Resin yields over time by tree size, Gainesville, 1994.

were not proportional to their 38 percent greater cross-sectional area. On a borehole area basis, the yield intensity for the standard borehole diameter (31.9 g/cm^2) was 13 percent greater than for the large hole (28.1 g/cm^2) (Table 5.4).

Table 5.4. Within-subjects comparison of resin yields for large and regular diameter boreholes at Hosford FL, Eastman and McRae GA sites, 1993.

Borehole Diameter (cm)	Yield Per Hole (g)	Yield Per Unit Hole Area (g/cm^2)
Large (3.49 cm)	996	28.1
Regular (2.54 cm)	822	31.9

n = 30 trees

The effect of hole depth on yields was examined with standard 2.54 cm diameter holes drilled 8.9 to 17.8 cm (3.5 to 7.0 inches) deep. Across all experimental data, holes greater than 11.4 cm deep produced higher yields (726, 673 g) than shallower holes (456 g). In 1992 experiments with systematic

manipulation and within-subjects controls at the Waldo and Hosford FL, and McRae GA sites, hole depths were examined at levels of 10.2, 14.0, and 17.8 cm. Again, yields for the two deeper hole groups (726, 776 g) were significantly greater than the shallowest hole (640 g), as summarized in Table 5.5. However, yields on a unit area basis were highest for the shallow holes (24.8 gm/cm^2), and lower for the medium and deep holes (20.3 and 17.2 gm/cm^2).

Table 5.5. Borehole yields by depth, Waldo and Hosford FL, and McRae GA sites, 1992.

Borehole Depth (cm)	Avg. Yield (gm)	Yield Per Unit Hole Area (gm/cm^2)
Shallow (10.2 cm)	640^b	24.9
Medium (14.0 cm)	726^a	20.3
Deep (17.8 cm)	776^a	17.2

Different superscripts indicate significantly different mean yields ($p<.05$).

Results in Gainesville (1994) experiments with hole drilling depths manipulated at very wide levels (8.9 vs. 17.8 cm) showed that yields for deep holes were substantially greater than shallow holes (Table 5.6). Moreover, within each treatment group, yields of shallow experimental holes were 109 g less than their control holes (406 vs. 515) compared to a difference of only 23 g between deep experimental holes and their respective controls. Yields for control holes were greater in trees with deep experimental holes, possibly due to the closer proximity between opposing holes in this case.

Table 5.6. Within-subjects comparison of borehole yields by hole depth, Gainesville FL, 1994.

Experimental Borehole Depth (cm)	Number of Trees	Average Seasonal Yield per Borehole (gm)		Difference Control - Exp (gm)
		Experimental Holes	Control Holes (8.9 cm)	
Shallow (8.9)	44	406	515	-109*
Deep (17.8)	24	580	603	-23

* Significant by paired t-test ($p<0.05$).

In summary, variation in both dimensions of hole areal extent (diameter and depth), were associated with higher yields, indicative of the greater capacity of resinous wood tapped, but the higher yields were not proportional to their greater area, as reflected by the diminution in yields per unit area. These findings are consistent with observations of yields as a function of wound size in conventional gum resin production operations (Snow, 1954), and support the hypothesis that pressure potential for resin exudation is reduced for larger boreholes.

Hole Orientation

Borehole yields by horizontal orientation with respect to the radial axis of the tree, are shown in Table 5.7. Yields for holes drilled at an angle of 45 degrees (735 g) were significantly higher than for radial holes (640 g; $p<.05$, Tukey's test). Moreover, yields for angled holes were increasingly greater at larger hole depths, and at depths of 17.8 cm, yields for tangential holes were over twice as great (Table 5.7). This pattern of results reflects the different compartment areas of the tree stem that are tapped by radial and tangentially oriented holes, and is consistent with the predicted sink effect of incipient heartwood in the core region of the tree.

Table 5.7. Borehole yields by horizontal orientation, Waldo and Hosford FL, and McRae GA sites, 1992.

Hole Orientation with respect to radial axis	Number of Holes	Average Borehole Yield (gm)			
		All Hole Depths	10.2 cm depth	14.0 cm depth	17.8 cm depth
Radial (0 deg)	267	640	635	680	363
Angled (45 deg)	426	735	653	743	807

In 1994 experiments at Gainesville FL, hole orientation in the vertical plane was examined by boring at a downward angle of approximately 45 degrees from the horizontal plane. Average yields for downward holes were significantly greater than horizontal holes (544 vs. 439 g), according to a univariate statistical test ($p<.05$). A within-subjects analysis comparing yields against the control hole revealed a difference of only 6 g (-42 vs. -48 g, Table 5.8), suggesting that downward holes enhanced yields for the opposing control hole.

Table 5.8. Borehole yields by vertical orientation, within-subjects comparison, Gainesville FL, 1994.

Experimental Hole Vertical Orientation (degrees from horizontal plane)	Number of Trees	Average Yield per Borehole (gm)		Yield Difference Control - Exp (gm)
		Experimental Holes	Control Holes	
Downward (45 deg)	21	544	586	-42
Horizontal (0 deg)	59	439	488	-48

Spacing Among Clustered Boreholes

Clustered borehole spacing patterns were studied for their effects on yields in two different experiments. At the Hosford site in 1993, holes were installed in three different patterns, illustrated in Figure 5.3: two new holes paired together approximately 10.2 cm apart ("paired"), holes evenly spaced around the tree's

circumference and midway between previously drilled holes ("evenly spaced"), and holes offset approximately 10.2 cm from a previous season's hole ("offset").

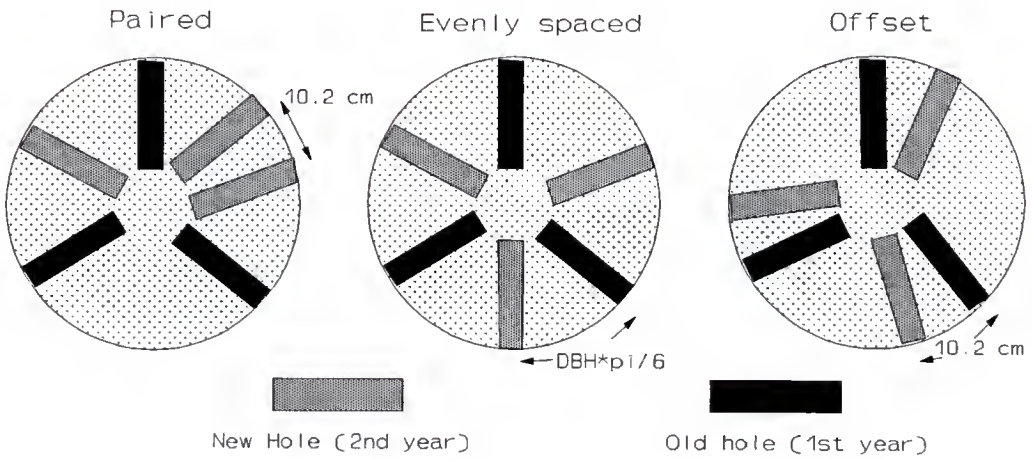

Figure 5,3. Borehole spacing patterns investigated, Hosford FL (1992-1993). Trees received same number of holes (10.2 cm deep) and same chemical treatment in two consecutive years.

As shown in Table 5.9, average yields for the "evenly spaced" and "offset" conditions did not differ (582 vs. 595 grams per hole), while the "paired" holes produced substantially less (430 grams). Although these differences were not statistically significant because of high variability, the direction of the results suggested that spacing between holes did affect resin yields.

Table 5.9. Resin yields by hole spacing pattern, Hosford FL site, 1993.

Hole Spacing Pattern*	Number of Holes	Yield Per Borehole (grams)	Yield Per Hole Per Day (grams)
Paired	24	430	2.16
Evenly-spaced	41	582	2.93
Offset	30	595	2.99

* Refer to Figure 5.3 for definitions of spacing patterns.

Experiments at Gainesville (1994) were designed with more levels of spacing treatments, with clusters of 2 or 3 holes made at "narrow" and "wide" horizontal separations between outer drill centers, resulting in four different combinations of hole numbers and spacings between adjacent holes, as previously described in Figure 4.2. These spacings were specifically selected to correspond to the extreme settings of the multi-spindle drill head adopted for mechanization of drilling operation, discussed in the final section. Results of this experiment are presented in Table 5.10. The effect of the treatment in each case is gauged by a within-subjects comparison of yields between the experimental and the single control boreholes. In general, yields for each hole varied consistently as a function of distance from other holes. In all cases, the control hole ("back position") produced a significantly higher yield than the average of the set of 2 or 3 holes on the opposite side of the tree ("left", "right", or "center" positions). Groups of two holes spaced 6 inches apart had essentially the same yields as control holes (465 vs 470 g), while groups of two holes spaced 9.53 cm had somewhat lower yields compared to controls (560 vs 616 g, Table 5.10).

Table 5.10. Resin yields for different numbers and spacings of clustered boreholes, Gainesville FL, 1994.

Experimental Condition*			Number of Trees	Total Hole Group Yield (gm)	Average Seasonal Yield Per Hole (gm)			
					Control Hole	Experimental Holes (2 or 3)		
Number of Clustered Holes	Vertical Spacing (in)	Horiz. Spacing (cm)				All Holes	Outer Holes	Center Hole
3	0	4.78	11	1163	525	387	445	314
3	0	7.62	11	1181	534	394	405	371
2	0	9.53	21	1121	616	560		na
2	0	15.20	41	929	470	465		na
3	1.88	4.78	15	1827	na	612	591	645
All Conditions			99	1289	522	502	493	460

Groups of three holes at both the 7.62 and 4.78 cm spacings had substantially lower yields compared to their control holes. Also, within groups of 3 holes, the hole in the "center" position produced lower yields than the outer holes ("left" or "right" positions), except for trees with 4.78 cm vertical spacing (Aug plot), where center hole yields were the highest at this site (645 g). Trees in this plot (Aug) were drilled by the mechanized drilling system with vertically offset boreholes, in the pattern shown in Figure 7.1. Total yields for groups of 2 or 3 experimental holes varied from 900 to over 1800 g, and differed significantly only on the basis vertical spacing, not on horizontal spacing or number of holes. The general yield depression effect as a function of hole number and spacing is evidence of mutual competitive interference between closely spaced holes, consistent with the hypothesis of a localized common source of resin in the tree, and the existence of a pressure potential effect as a function of tapping intensity. The higher yield of the center hole when there was a vertical separation may be attributed to increased xylem water potential, chemical stimulation, or reduced capacity interference in the zone around these holes, below the two outer holes. Vertical separation of boreholes is an opportunity to overcome the yield depressing effects of hole clustering envisioned for mechanized systems.

Chemical/Biological Treatment Effects

Treatments with 2-chloroethyl phosphonic acid (CEPA) affected borehole resin yields consistently and significantly across all experiments during 1991-94. CEPA levels greater than .05 ml a.i. per hole produced yields averaging 643 to 722 g compared to 352 to 360 g for the lowest treatment level or no CEPA (Table 5.11). CEPA treatments also significantly affected yields on a whole-tree basis, with yields for the trees receiving any CEPA treatment 3 to 4 times greater than for

trees with no CEPA treatment. Thus, CEPA appeared to have both localized and systemic effects, and to have a threshold level for enhancing yields.

Table 5.11. Borehole resin yields by CEPA treatment level, 1991-1994.

CEPA Dose (ml/hole)	Number of Holes	Cumulative Final Yield (gm)	
		Mean	SE
none	97	352[b]	27
low (<.05)	20	360[b]	50
medium (.05-.10)	458	643[a]	17
high (.10-.15)	461	706[a]	20
very high (>.15)	301	722[a]	25

Different superscripts indicate significantly different means ($p<.05$, Tukey's test).

To resolve whether higher levels of CEPA treatment resulted in proportionately higher yields, data were separately analyzed for 1994 experiments where CEPA dosages were more widely varied, the chemical treatment was applied more precisely with a fixed-displacement type sprayer, and a within-subjects contrast was available from the control hole. Results of 1994 experiments by CEPA treatment are summarized in Table 5.12. Experimental holes with equal or higher CEPA levels than control holes (.05 to .07 ml a.i.) had yields comparable to the controls, while those with lower CEPA levels had significantly depressed yields. Thus, these results confirm that a threshold dosage of about 0.05 ml CEPA per hole was sufficient to produce good yields, but there was marginally less effect at higher levels.

Table 5.12. Borehole resin yields by CEPA treatment level, within-subjects comparison, Gainesville FL, 1994.

CEPA Dose Experimental Hole compared to control hole dose of 0.07 ml)	Number of Trees	Cumulative Final Yield (gm)		
		Experimental Holes	Control Hole	Difference
lower (0.035)	8	363	690	-327
equal (0.070)	51	472	479	-7
higher (.14 to .16)	21	455	525	-70
very much higher (.28)	4	718	725	-7

Sulfuric acid had widely variable and mixed effects on borehole tapping yields, which were confounded with site, year, and plot effects. Average yields for high dosages of sulfuric acid did not significantly differ from average yields for no acid, but acid treatments strongly interacted with CEPA treatments. Since both CEPA and sulfuric acid are strong acids, it is reasonable that their effects were complimentary in altering the chemistry of the borehole wound environment for breakdown of CEPA into ethylene.

Experimental boreholes which received treatment with a sterilized culture extract of the Blue stain fungus (*Ophiostoma*) had lower average yields than those without (372 vs 479 g, n=30), but according to a within-subjects analysis, there was no effect of extract treatment. The positive effect of this treatment on resin flow reported by Popp et al. (1991) was over a short time period of 2 days.

Effects of Collection Container Type

To measure the effect of reduced container pressure on yields, a controlled study was performed in 1994 at McRae GA, from August 2 to November 9 (99 days), with each of 21 trees receiving 2 boreholes treated uniformly (10.2 cm depth, radial orientation, 7.5% CEPA) except that one borehole was fitted with a 2-

liter PET bottle while the other had a spout-bag device installed. The average yield for boreholes with a spout-bag device (1173 g) was 19 percent greater than yields for holes with bottles (983 g) (Table 5.13).

Table 5.13. Borehole yields collected in 2-liter PET bottles and spout-bag apparatus, McRae GA, 1994.

Container	Seasonal Yield (gm)	
	Mean	SE
2-liter PET bottle	983	57
spout-bag apparatus	1173	77

This difference was highly significant according to a paired t-test ($p<.01$). The magnitude of this effect may have been emphasized by the generally very high yield levels of these trees, which resulted in many of the 2-liter bottles becoming nearly filled, so that a high pressure was developed in the bottles.

This experiment showed that pressure potential can affect yields from borehole tapping, since this was the only variable that differed for the two container types. The average volume of resin collected in bottles was calculated at 923 cc (at a resin density of 1.065 gm/cc), leaving a gas headspace of 1077 cc in the 2 liter bottles. This represented a 1.86 compression ratio of the headspace gas in the bottle (2000/1077 cc), or a pressure of 1.86 atmospheres, assuming no leakage occurred. The relative system sensitivity, in terms of rate of change in yield (190/1173 gm) with respect to the change in pressure (.86/1.00 atm), was 19 percent.

Effects of Time of Year

Cumulative final yields for separate plots established at the Gainesville site in 1994 are plotted in Figure 5.4. Yields generally followed the annual heating cycle,

and peaked in the August plot. Table 5.14 summarizes seasonal effects of borehole tapping. Borehole yields in the plot established in August were significantly higher than for the other three phases, which did not differ. This result is consistent with observations of conventional resin production, with peak yields obtained during July and August (Clements, 1961; Harper and Wyman, 1936). Higher yields for the August plot were also associated with the yield-enhancing effect of the 4.8 cm vertical offset between the center and outside holes, as discussed previously.

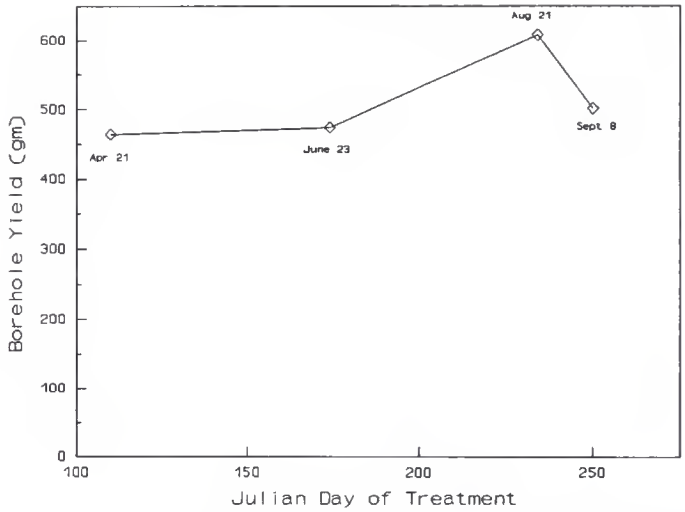

Figure 5,4. Resin yields by Julian date of treatment, Gainesville, 1994.

Table 5.14. Borehole resin yields by time of year installed, Gainesville FL, 1994.

Time of Year Installed (experimental plot)	Num Holes	Borehole Yield (gm)		Num Trees	Tree Yield (gm)	
		Mean	SE		Mean	SE
April 21 to Oct. 15	60	464[b]	38	20	1393	161
June 23-25 to Nov. 27	144	474[b]	33	44	1552	152
August 21-25 to Dec. 31	44	608[a]	54	15	1827	232
September 8 to Dec. 31	70	502[b]	34	20	1758	188

Different superscripts indicate significantly different mean yields ($p<.05$, Tukey's test).

Weather patterns during the period of this experiment did not account for the differences in yields between plots in a predictable fashion. Average daily

temperatures during the first month following borehole treatment were higher for the June plot (27.0 deg C) than the August and September plots (25.7, 24.4 deg C), while rainfall was higher for the September plot (0.43 cm/day) than the June or August plots (0.18, 0.28 cm/day). This suggests that differences in inherent seasonal resin productivity and treatment effects were responsible for the yield differences observed among plots.

Yields for A Second Year of Production

Trees tapped for two consecutive seasons at the Hosford site (1992-93) with identical treatments and numbers of holes resulted in slightly lower average yields in the second year. As shown in Table 5.15, average yield per tree declined 13 percent, and average yield per hole declined 17 percent. These differences were statistically significant with a paired t-test ($p < .05$). These results are evidence of alteration in the capacity for resin production by borehole tapping, and suggest that long-term borehole tapping with a series of treatments may suffer from reduced yields in latter years.

Table 5.15. Yields for borehole tapping trees in two consecutive seasons, Hosford FL, 1992-1993.

Year	Yield Per Tree (grams)	Yield Per Hole (grams)	Yield Per Hole Per Day (grams)
1992	1614	642	5.49
1993	1407	535	2.69

n = 37 trees

Resin Flow Rates Over Time Since Treatment

Cumulative resin yields over time in 3 plots at Gainesville FL (1994), at 7 days, 23 to 28, 50 to 51, and 99 to 147 days following borehole treatment, are summarized in Figure 5.5. The higher average yields for the August plot (Table 5.14), were evident within 28 days after borehole treatment, and were maintained for the rest of the experiment. The duration of resin flow observed for borehole tapping was several-fold longer than typically occurs for conventional open-face production methods, and is a key to the higher productivity of this system, just as prolongation of flow was a key innovation for acid paste treatments in conventional gum resin production.

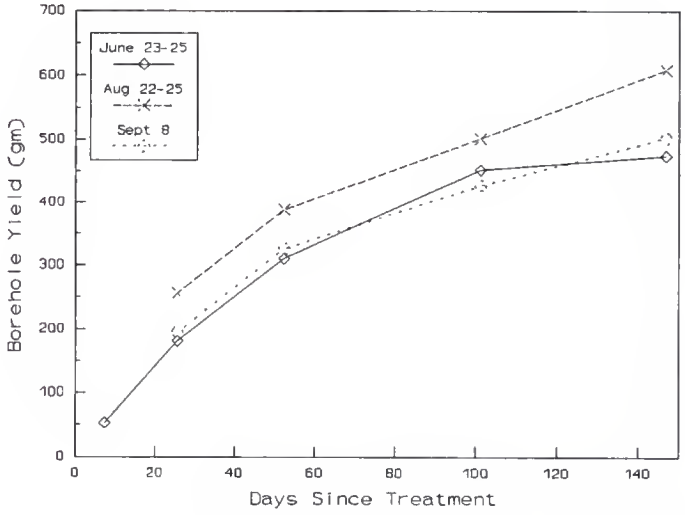

Figure 5,5. Cumulative resin yields over time for experimental plots at Gainesville FL (1994).

All data for resin yields over time are plotted in Figure 5.6, expressed as a percentage of the final cumulative yield. The exponential function plotted in Figure 5.6 was fitted to the data by least-squares regression (SAS Inst., 1988) using the model shown in Equation 5, where $Y_{t(days)}$ is the cumulative yield measured at time t = days, Y_F was the cumulative final yield, and -0.0189 was the fitted parameter.

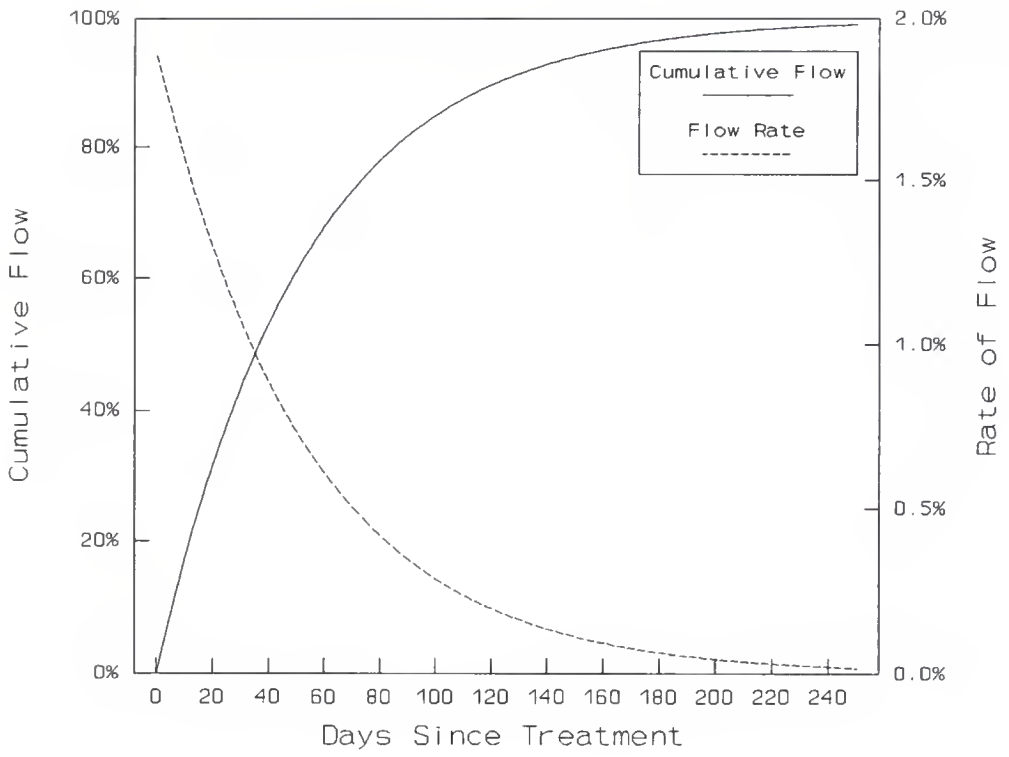

Figure 5,6. Plot of cumulative resin flow and flow rate over time since treatment (days), expressed as a fraction of final cumulative flow, Gainesville FL, 1994.

$$Y_{t_{days}} = Y_F \times (1 - e^{-.0189 \times Days}) \quad (5)$$

This regression model explained 92 percent of variation in cumulative resin flow over time as a share of total flow ($r^2 = .922$, $n = 914$), given that the total flow was known. The time constant for this function, the point at which two-thirds of the final flow had been reached, calculated as the inverse of the exponential parameter, was 53 days. The equation predicts that 90 percent of total flow was reached at approximately 120 days, and 95 percent at about 180 days. The high reliability of this flow rate function, is noteworthy, and is confirmation of the capacitance and pressure potential source-limited nature of the borehole resin

production system. The rate of daily resin flow over time is shown in Figure 5.6 as a percentage of final flow.

An expression for the instantaneous rate of flow is represented by the first derivative of the fitted equation for cumulative flow as a function of days is shown in equation 6, with terms the same as defined previously (equation 5).

$$\frac{\partial Y}{\partial t_{days}} = -.0189 \times Y_F \times (1 - e^{-.0189 \times Days}) \qquad (6)$$

This flow rate function represents the marginal value of resin production over time. A marginal value function over time is plotted in Figure 5.7 for an expected tree yield of 2.0 kg and a product value of $.60 per kg.

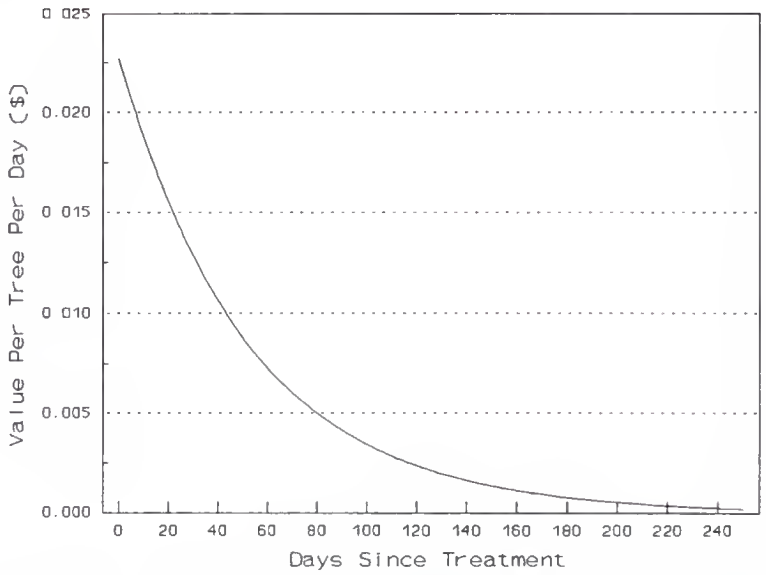

Figure 5,7. Marginal value function for resin flow over time.

This example shows that for a daily cost of $.005 for use of the tree, the optimal production period is about 80 days. A higher yield level or product price would shift the curve to the right, resulting in a longer optimal production period.

All experimental treatment and resource quality effects previously noted for seasonal resin yield results were also present in the intermediate time yield results. A repeated measures analysis of variance on cumulative resin yields at each period showed significant effects for hole vertical orientation, tree size and tapping intensity (F test, $p < .05$).

The exponential-decay time function for resin yields was separately analyzed and fitted by non-linear least-squares regression for subgroups of data. Results for the three experimental plots in which time-course measurements were made, are presented in Table 5.16. Plots established later in the season (August and September) had relatively more rapid initial flow and rapid decay, indicated by higher estimated values for the exponential function coefficient, and correspondingly lower values for the number of days to achieve two-thirds of total flow.

Table 5.16. Parameters and statistics obtained for non-linear least squares analysis of cumulative resin flow over time, Gainesville FL, 1994.

Experimental Plot (Date)	Exponential function Parameter Estimate (eq.5)	Days to achieve 67% of total flow	Number of Observations	Model Coefficient of Determination (r^2)
June 21	0.0176	56.9	572	.920
August 24	0.0200	50.0	132	.915
September 8	0.0207	48.3	210	.936
All	0.0189	52.9	914	.922

High initial flow rates and rapid decay were associated with shallow rather than deep hole depths and horizontal rather than downward-oriented holes. The slower flow response of downward holes is partly attributed to the necessary hole-filling volume required before external flow occurs. Chemical treatment levels affected flow rates, with higher CEPA levels bringing about a prolonged flow, as well as increased total yield.

Yields by Compartment Area

Yields per unit tree cross sectional area were analyzed separately for "hole", "outer", and total "sector" compartment areas. Over all data from 1991-94,

borehole yields averaged 8.5 g cm^{-2} of tapped sector area, 22.9 g cm^{-2} hole area, 33.9 g cm^{-2} outside area, and 42.3 g cm^{-2} inner area. Results for resin yields expressed on a unit area basis generally showed the same pattern of treatment effects as did the raw data for borehole yields, but a somewhat different pattern for experimental sites, due to corrections for tree size as a confounding variable across sites. Yield per unit sector area and outer area were significantly higher for the Hosford site, while yields for the Gainesville and McRae sites were not significantly different, as shown in Table 5.17.

Table 5.17. Borehole resin yields per unit compartment area, by site, 1991-94.

Experimental Site	Num Holes	Yields Per Unit Area (gm/cm^2)					
		Sector Area		Hole Area		Outer Area	
		Mean	SE	Mean	SE	Mean	SE
Gainesville FL	318	7.3^{b}	0.3	19.8^{ab}	0.8	28.2^{bc}	1.7
Waldo FL	102	5.0^{c}	0.5	17.1^{b}	1.1	20.2^{c}	1.9
Hosford FL	247	11.9^{a}	0.5	24.1^{a}	0.8	49.4^{a}	2.0
McRae GA	603	8.2^{b}	0.3	24.6^{a}	0.6	33.3^{b}	1.9
Soperton GA	24	8.8^{b}	1.2	18.4^{b}	2.6	27.4^{bc}	4.5
All sites	1337	8.5	0.2	22.9	0.5	33.9	1.1

Superscripts indicate significantly different means ($p<.05$, Tukey's test).

Analysis of Tree Tapping Intensity

Borehole yields per unit compartment area were analyzed in relation to tree tapping intensity, calculated as the ratio of borehole sector area to tree basal area. Area-specific yields generally declined with increasing tapping intensity, as shown in Table 5.18. Yields for low and medium tapping intensities (less than 30%) were significantly higher than yields for high or very high tapping intensities (greater than

30%). These results support the conclusion that resin flow pressure potentials are inversely related to the extent of borehole tapping treatments.

Table 5.18. Borehole resin yields per unit compartment area, by tree tapping intensity, slash pines, 1991-94.

Tree Tapping Intensity (sector area tapped/tree basal area, cm^2/cm^2)	Num Holes	Yields Per Unit Area (gm/cm^2)					
		Sector Area		Hole Area		Outer Area	
		Mean	SE	Mean	SE	Mean	SE
low (less than 15%)	367	13.6[a]	0.5	27.9[a]	1.0	58.9[a]	2.8
medium (15 to 30%)	277	9.1[b]	0.3	24.3[a]	1.0	33.9[b]	1.7
high (30 to 45%)	375	5.7[c]	0.2	20.5[b]	0.6	21.4[c]	1.0
very high (over 45%)	255	4.5[c]	0.2	17.1[b]	0.6	16.4[c]	1.0

Superscripts indicate significantly different means within experimental condition ($p<.05$, Tukey's test).

Yields per unit area were analyzed as non-linear functions of unit area, using the model shown in equation 7, where Y_A is the cumulative yield per unit area (gm/cm^2), and the parameters B_0 and B_1 were fitted by least squares regression.

$$Y_A = B_0 \times e^{(-B_1 \times A)} \qquad (7)$$

The function for expected hole yields per unit sector area tapped as a function of sector area tapped, is plotted in Figure 5.8 along with upper and lower 95 percent confidence intervals. This model had a coefficient of determination of 71 percent ($r^2 = .710$).

Borehole yields were predicted from this relationship as the product-moment of the extensive variable (sector area tapped) and the intensive variable (expected hole yield per unit sector area), resulting in a bitonic function with a peak borehole yield of about 775 g at about tapping extent of 110 cm^2 of tapped sector area. This implies that tapping an area too large results in reduced yields.

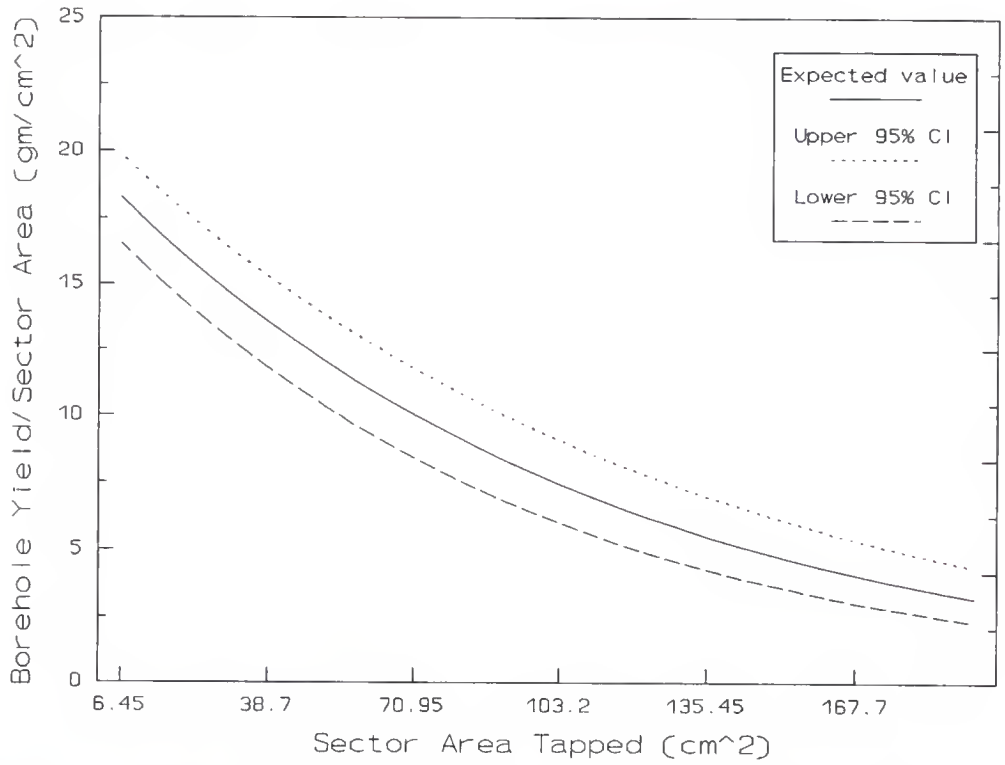

Figure 5,8. Borehole resin yield intensity per unit sector area (gm/in^2), and predicted hole yield (gm) as a function of sector area tapped (in^2), 1991-94.

Expected hole yields per unit area of "hole" and "outer" compartments showed similar exponentially declining trends as a function of unit areas. Model parameters and statistics for all yield per unit area analyses are summarized in Table 5.19. Predicted hole yields as a function of hole area tapped were monotonically increasing over the range of experimental data, peaking at 45 cm^2, corresponding to hole depths of 17.8 cm.

Table 5.19. Model parameters and statistics for borehole yields per unit area (g/cm^2) as a non-linear function of unit area (cm^2), slash pines, 1991-94.

Compartment Area	Parameter Value (eq. 7)		Coefficient of Determination (r^2)
	B_0	B_1	
Sector Area	19.4	0.0093	.710
Hole Area	36.1	0.0155	.716
Outer Area	138.7	0.0713	.639

Borehole yields per unit area were also analyzed as a declining exponential function of tapping intensity, defined as the fraction of tree cross-sectional area tapped. These analyses generally resulted in narrower confidence intervals, and slightly larger coefficients of determination (Table 5.20). The model based on sector area predicts a maximum borehole yield of about 0.74 gm/cm^2 of tree area tapped at a tapping intensity of about 11 percent of the tree cross-sectional area.

Table 5.20. Borehole yield intensity per unit area (g/cm^2) as a function of tapping intensity index (cm^2/cm^2), non-linear model parameters and statistics, 1991-94.

Compartment Area	Parameter Value		Coefficient of Determination
	B_0	B_1	(r^2)
Sector Area	19.8	1.502	.719
Hole Area	30.1	0.439	.728
Outer Area	116.4	2.528	.600

Resin yields were analyzed in similar fashion on a whole-tree basis, representing the sum of all borehole yields and tapped compartment areas, with results similar to those obtained on an individual borehole basis. Tree resin yields per unit sector area tapped are plotted as a function of tree tapping intensity in Figure 5.9. A declining exponential function fitted to these data had a coefficient of determination of nearly 75 percent ($r^2 = 0.749$). The fitted curve for yield per unit sector area as a function of tapping intensity is shown in Figure 5.10. The predicted borehole yield per unit tree area (gm/cm^2) plotted in Figure 5.10 (right axis) was calculated as the product moment of tapping intensity (horiz. axis) and expected yield per unit sector area (left axis). This function for tree yield per unit sector area tapped predicts a yield of about 7.0 gm/cm^2 at an optimal tapping intensity of about 30 percent of tree stem area.

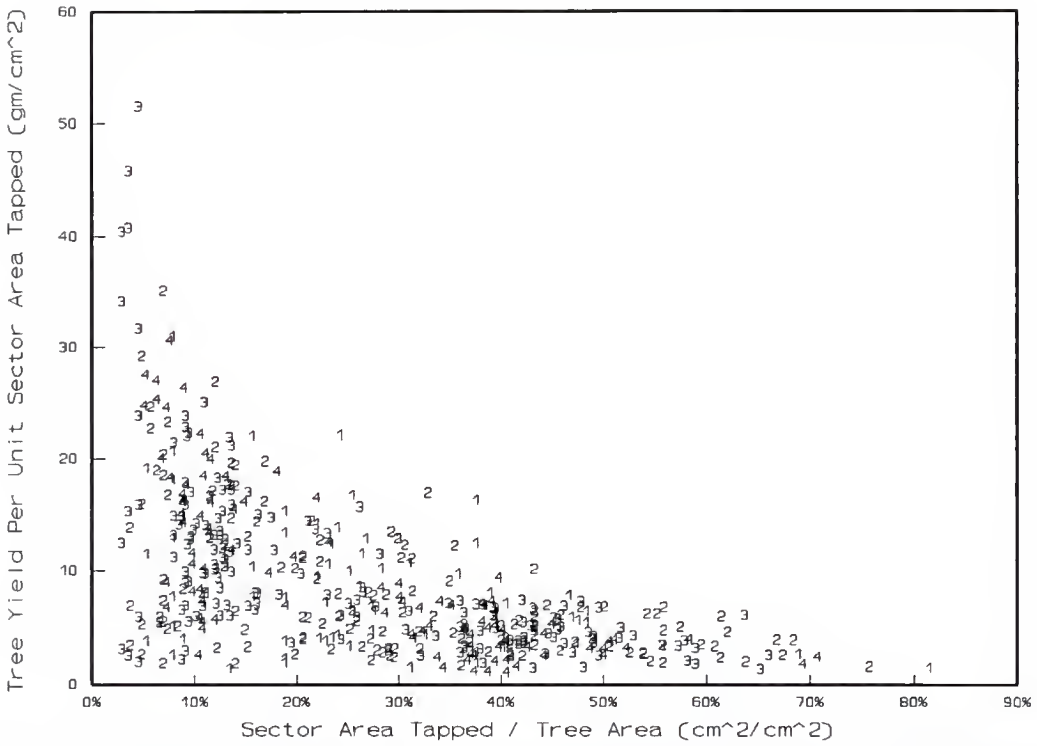

Figure 5,9. Tree resin yields per unit sector area tapped as a function of tree tapping intensity, borehole-tapped slash pines, 1991-94, plotted with numbers representing tree sizes (1, 2, 3, 4), from small to large, respectively.

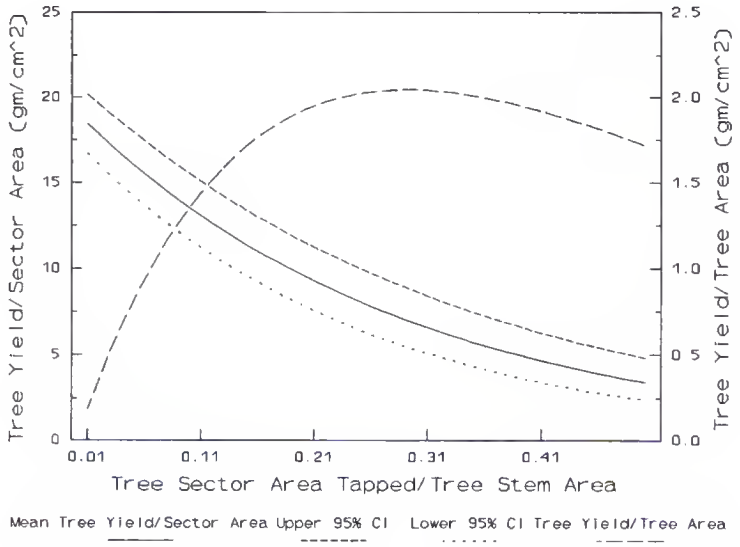

Figure 5,10. Tree resin yields per unit sector area borehole-tapped (expected value +/- 95% confidence interval), and predicted total tree yield as a function of tapping intensity.

Response Surface Analysis and Treatment Optimization

Response surface analysis of borehole resin yields on a whole-tree basis with respect to tapping intensity and CEPA dosage (combined for all holes) resulted in a model with a moderately high coefficient of determination ($r^2 = 0.425$, $df = 483$). Linear, quadratic, and crossproduct terms in the model were all statistically significant (F test, $P < .05$).

Ridge analysis of the response surface with respect to tree sizes showed that treatments which produced maximum yields differed only slightly, as shown in Table 5.21, indicating a relative insensitivity of yields to treatment levels near the optimum. CEPA treatment levels were somewhat more sensitive, with the optimal dosage ranging from 0.36 to 0.48 ml (a.i.) for small to large trees, 23 to 36 cm dbh (9 to 14 inches). Because expected tree yields were not very sensitive to deviations from the optimal tapping intensity, a uniform tapping treatment for the range of tree sizes likely to be encountered in a forest stand will probably result in tapping intensities that robustly produce near-optimal yields.

The predicted tree yields for the optimal tapping treatments are generally higher than predicted by the non-linear model shown in Figure 5.10, due to the global optimization performed by the ridge analysis procedure, but are within the range of experimental data.

Table 5.21. Predicted treatment levels for maximizing tree yields as a function of tree diameter, from ridge analysis of response surface, slash pines, 1991-94.

Tree Diameter (DBH)		Optimal Treatment Level		Estimated Tree Yield (gm)
inches	cm	CEPA dosage (ml/tree a.i.)	Tapping intensity (sector area tapped/tree area)	
9.0	22.9	0.360	0.420	1520
9.6	24.4	0.359	0.424	1670
10.1	25.7	0.362	0.426	1817
10.7	27.2	0.369	0.425	1963
11.3	28.7	0.380	0.422	2112
11.8	30.0	0.393	0.419	2263
12.3	31.2	0.408	0.416	2419
12.9	32.8	0.424	0.409	2579
13.4	34.0	0.441	0.404	2745
13.9	35.3	0.459	0.398	2916
14.4	36.6	0.477	0.392	3093

Productivity Comparisons With Traditional Systems

Because borehole tapping is a fundamentally new method of gum resin production, it is appropriate to compare its productivity with traditional systems. Table 5.22 summarizes typical yields, treatment frequencies and yields per treatment reported for various production systems with slash pine in the Southeast US. For a typical tree (25 cm dbh), yields from wood chipping and bark chipping methods ranged from 3.7 to 7.3 kg annually, for 8 to 33 treatments. The predicted yield from a single borehole tapping under optimal treatment conditions (1.8 kg), represents a yield per treatment nearly twice as great as the bark chipping method with acid-CEPA paste treatment (1800 vs 918 g, Table 5.22). Thus, the borehole resin production system offers significantly greater labor productivity than

traditional systems, but sacrifices overall tree productivity for extended production periods.

Table 5.22. Average yields, number of treatments, and yield per treatment for different resin collection systems with Slash Pine in the Southeast US.

Technology	Treatment method	Seasonal Tree Yield (kg)	Number of Treatments per year	Treatment Interval (days)	Yield per Treatment (gm)
Wood chipping[1]	1.27 x 1.27 cm streaks 1/3 circumference	3.68	33	7	111
Bark chipping[2]	50% H_2SO_4 spray, 1.9 cm streaks 1/3 circumference	5.33	17	14	314
Bark chipping[3]	50% H_2SO_4 and 15% CEPA paste, 3.8 cm streaks 1/3 circumference	7.34	8	28	918
Borehole tapping	3-2.5 x 10 cm holes, .36 ml CEPA	1.80	1	na	1800

Yields represent 25 cm DBH trees.
[1] Harper and Wyman, 1936; Schopmeyer and Larson, 1955
[2] Bengston and Schopmeyer, 1959
[3] McReynolds and Kossuth, 1984

SECONDARY EFFECTS OF BOREHOLE TAPPING

Effects on Tree Growth

Average annual radial growth rates of borehole-tapped trees and matched untapped controls (McRae 1992 plot) did not substantially differ during a 2-year period since tapping (Table 6.1). Tapped trees had slightly higher overall growth rates both before and since tapping, and both groups had greater growth during the latter 2 year period than the prior 3 year period, but the acceleration in growth since tapping was equal (30%) for both groups. These trees were tapped from July to October, a period when growth effects of resin production have been reported most marked (Schopmeyer and Larson, 1954). These results indicate that borehole tapping on this above-average quality site (SI = 84) did not adversely affect tree growth rates during this particular period when growth rates were relatively good. It is possible that a growth reduction due to tapping could be observed at times of less favorable growing conditions, or on extreme sites.

Table 6.1. Annual radial growth rates of borehole tapped and non-tapped slash pines, before and since tapping, McRae GA, 1989-1993.

Growth Period	Average Annual Radial Increment (mm)			
	Tapped Trees (n = 41)		Control Trees (n = 25)	
	Mean	SE	Mean	SE
Before Tapping (3 yrs, 1989-91)	2.73	0.16	2.49	0.18
Since Tapping (1.7 yrs, 1992-93)	3.55	0.17	3.25	0.20
Change	0.82	0.10	0.76	0.05

Tree radial growth was inconsistently correlated with borehole yields. For the trees tapped in the McRae (1992) experiment, 5 year growth was negatively correlated with borehole yields (r = -22%). In Gainesville (1994) experiments, growth was moderately positively correlated with resin yields (r = 32%), but this relationship was confounded by the correlation between tree size and growth rates.

Tree Stress Effects

Minor browning and leaf loss occurred in approximately 5 percent of borehole tapped trees during experiments from 1991 to 1993, generally associated with high levels of CEPA treatment. Some defoliation of the canopy was observed in 85 percent of trees in the April plot at Gainesville (1994). Three trees (15%) were completely defoliated and two later died, while most others that suffered less than 50 percent defoliation generally recovered. Trees in this plot were the earliest that had ever been tapped in the springtime, and received a rather high dose of CEPA (.45 ml), though not greater than many other trees in later plots. The seasonal effect of CEPA-induced tree stress is probably a function of more rapid uptake and translocation of the chemical to the tree's canopy during the period of rapid growth between March and May in the southern US. CEPA chemical levels for borehole treatments during this period should be reduced to minimize excessive stress effects. Defoliation was more severe for smaller trees, presumably because they have less buffering capacity against chemical treatments.

Attacks by Black Turpentine beetles (*Dendroctonus terebrans*) were also much more severe during 1994 than at any previous time. As many as 15 separate beetle attacks (pitch tubes) were counted on individual trees. BTB attacks were not clearly associated with CEPA-induced stress levels, but were most intense near the edges of plots, where beetles were intercepted as they moved into the stand. Some

attacks by *Ips* beetles were also observed, and in all cases resulted in tree death. It is possible that the unprecedented level of insect attacks observed in 1994 were related to greater emissions of attractant terpenes from the spout-bag collection devices than from the PET bottles.

Observations of defoliation and beetle attacks were summarized as a composite rating of tree stress, with 3 levels: "severe" for trees with over 30 percent defoliation, more than 5 BTB attacks, or *Ips* beetle attack; "moderate" for trees with 1 or 2 BTB attacks or up to 30 percent defoliation; and "none". Resin yields were significantly different for these tree stress categories as shown in Table 6.2. Yields for ostensibly unstressed trees were nearly 3 times greater than for severely stressed trees.

Table 6.2. Summary of borehole resin yields by tree stress level, Gainesville (1994).

Tree Stress Category	Number of Trees	Avg. Borehole Resin Yield (gm)	Avg. Tree Yield (gm)
None: no BTB attacks, no defoliation, no Ips attacks	41	592[a]	1878[a]
Moderate: up to 5 BTB attacks or up to 30% defoliation, no Ips attacks	50	474[b]	1514[b]
Severe: 5 or more BTB attacks or over 30% defoliation, or Ips attack.	8	216[c]	664[c]

Superscripts indicate significantly different means ($p<.05$, Tukey's test).

It was observed that BTB attacks often resulted in a rapid reduction in resin flow rates. A within-subjects, repeated measures analysis of variance (SAS GLM) indicated that incidence of BTB attack was a highly significant factor affecting resin yields over time ($p<.001$). Figure 6.1 shows that resin yields for severely stressed trees were nearly equal to less stressed trees during the first month after treatment, but flow rates were reduced during the second and third months. This result is consistent with other reports of reduced oleoresin flow and oleoresin exudation

pressure in trees under severe stress from drought or insect attack. There was no evidence, however, that moderate levels of stress, indicated by some defoliation or beetle attack, resulted in greater yields as predicted.

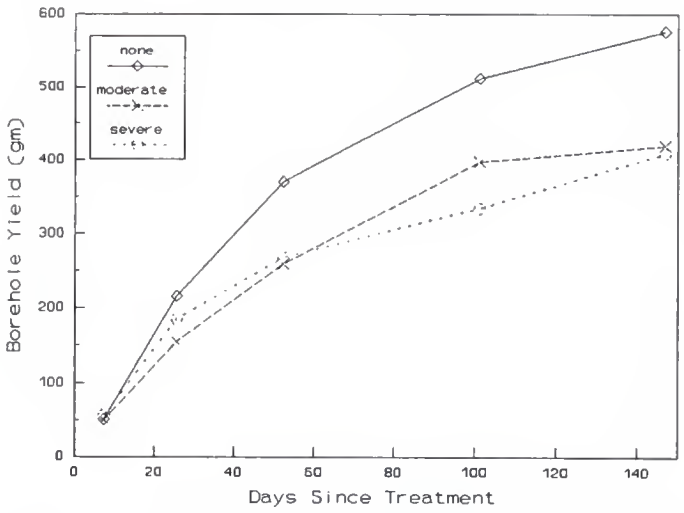

Figure 6,1. Borehole resin yields over time, by tree stress level, Gainesville, 1994.

Tree mortality due to borehole tapping has generally been very low, with less than 1 percent dying for any reason during 1991-93 studies. At the Gainesville site in 1994, 3 of 20 trees (15%) in the April plot eventually died as a result of severe defoliation due to CEPA treatment, and subsequent attack by Black Turpentine Beetles and *Ips* beetles. This was the highest mortality observed to-date, and is probably representative of extreme environmental conditions. The Gainesville area suffered an unprecedented epidemic of the Southern Pine Beetle that killed a substantial part of the urban pine forest in 1994.

Deposition of Extractives

Deposition of extractives in the tree stem due to borehole tapping not only provides insight to the mechanisms of borehole resin flow, but is important for subsequent utilization of the wood. A small sample of trees were sacrificed and sectioned at regular intervals to examine and photographically document the pattern of resin deposition around boreholes. Figure 6.2 shows the extent of resin deposition around boreholes in a tree which had been tapped with two boreholes.

Resin soaking occurred approximately 0.5 to 1.0 cm around the margins of holes in a horizontal plane. For the hole drilled at an oblique angle with respect to the tree's radial axis, resin soaking also extended horizontally from the hole to the tree's center in a pie-shaped sector and extended vertically about 75 cm above the hole, but not below. This demonstrates that borehole tapping can cause extensive resin deposition in the tree, although the incidence of this phenomenon is unknown. The yield from the hole with extensive resin deposition was significantly less than for the opposing hole, suggesting that resin in this part of tree was diverted into a low pressure sink. The greater vertical extent of resin deposition is consistent with the patterns described by Shigo (1979), and suggests that cavitation of the water conducting pathways occurred above the taphole. The time-course of resin deposition is not known, or whether significant resin flow occurs after deposition.

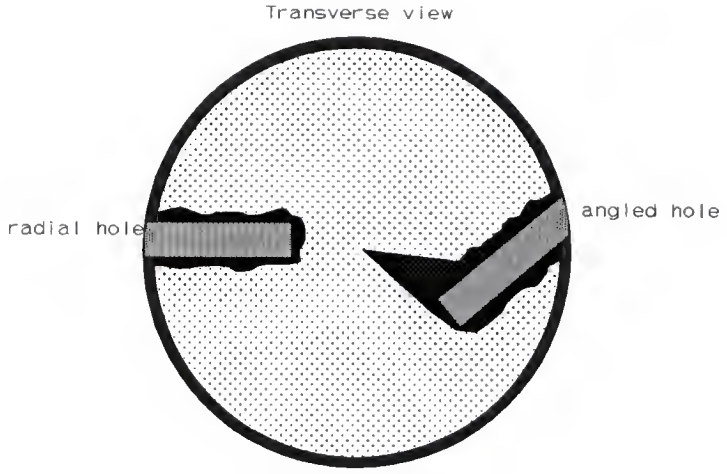

Figure 6,2. Illustration of resin deposition around radial and angled tapholes. Cross section at hole level.

Green and dry wood densities for inner and outer portions of radial increment cores measured for 18 trees are summarized in Table 6.3. The outer section of cores from above boreholes had a significantly higher density than their corresponding inner sections ($p < .05$, t-test). Densities of the core sections from the "middle position" on the tree did not differ from each other or from the inner section of the core above the borehole. So, the wood above boreholes had some

resin deposition due to the tapping treatment, but this effect did not extend laterally or centripetally to the inner section of the core.

Table 6.3. Tree increment core densities, Gainesville FL, 1994

Core Position	Core Section	Avg. Density (gm/cc) Fresh	Dry (48 h)
Above Hole	Inner	0.927	0.643[a]
	Outer	1.061	0.832[b]
	All		0.772
Between sides	Inner	0.928	0.696[a]
	Outer	0.933	0.659[a]
	All		0.674

n = 18 trees

Analysis of monoterpenes in increment core wood samples for 3 trees are summarized in Table 6.4. Total monoterpene concentrations on a whole-tissue basis averaged 0.058 mg per g dry weight. These results indicate a very low level of monoterpenes compared to other published figures (eg. Lewinshohn et al. 1991), and suggest that the chemical defensive status of the tree was not in a strongly activated induced response state.

Table 6.4. Monoterpene concentrations in woody tissue of increment core samples from 3 borehole-tapped trees, 1994.

Monoterpene	Concentration (mg/g d.w.)
alpha pinene	0.034
camphene	0.001
beta pinene	0.016
myrcene	0.001
limonene	0.001
beta phellandrene	0.006
total identified	0.058

Physico-Chemical Properties of Oleoresin

Resin from borehole tapping was naturally found to be very clean and free of gross contaminants, with less than 1 percent losses (Table 6.5). It was also extremely clear (X grade), and ranged from a light amber color to nearly colorless. The turpentine fraction of borehole samples (21.8%) was somewhat higher than for regular crude oleoresin (15%), which can probably be accounted for by the capture of volatiles that are normally lost with the open-face production system (Wyman, 1932). Virgin xylem oleoresin from untapped slash pines has been widely reported to contain 20 to 30 percent monoterpenes, so there was no evidence of heightened monoterpene levels in borehole-tapped trees. There was no significant difference in the turpentine fraction among resin sample groups from trees receiving different levels of CEPA and H_2SO_4 treatments, as was found for CEPA treatments in conventional resin production (Kossuth and McReynolds, 1987). High levels of monoterpenes facilitate resin flow by lowering viscosity (Runckel and Knapp, 1946), but are not a sufficient condition for borehole resin production, since samples of borehole-produced resin from the low-yielding Maritime pine (*P. pinaster*) in France contained very high levels of turpentine (27 to 35%).

Table 6.5. Gross composition of borehole-produced oleoresin, slash pine.

Fraction	Percentage
Rosin (diterpenes)	77.2
Turpentine (monoterpenes)	21.8
Other (loss)	0.9

An acetone crystallization test showed that borehole-produced rosin from slash pine and *Pinus oocarpa* were free of crystallization, as is the regular rosin

from these species. Tests of resin from other species (*P. palustrus, P. pinaster, P. caribea*) showed rapid crystallization. Since slash pine and *P. oocarpa* were the only two species which produced high borehole yields, the inherent tendency of resin acids to crystallize is probably in part responsible for species differences in borehole resin yields.

Analysis of the resin acid composition of borehole-produced resin by liquid-gas chromatography showed a higher percentage of pimaric, levopimaric and palustric, isopimaric, and dehydroabietic resin acids compared to regular WW American rosin (Figure 6.3). The bottle-collected rosin had a lower percentage of abietic and other resin acids than regular WW rosin. It was reported by industrial users that borehole-produced rosin was highly reactive, which is a valuable property for manufacturing modified resins, since less material is needed as a reactant (Jim Feltham, Akzo Coatings, Baxley, GA).

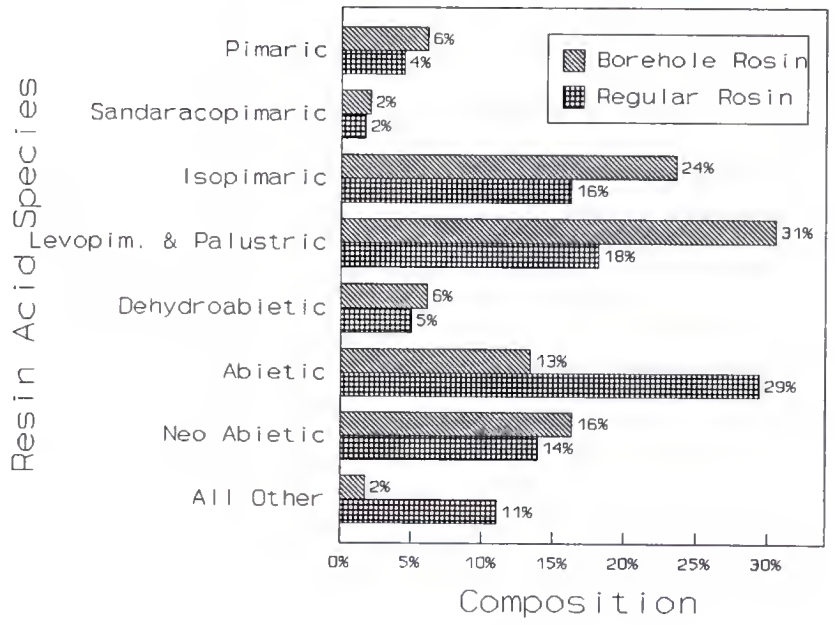

Figure 6,3. Resin acid composition of borehole-produced rosin vs. conventionally produced American rosin (WW grade).

MECHANIZATION OF BOREHOLE RESIN PRODUCTION OPERATIONS

Mechanization of borehole tapping operations was pursued during 1994 to implement the findings from experimental analysis of the borehole tapping system, for successful commercialization of the technology.

Need for Mechanization of Borehole Tapping

The concept of a mechanized borehole tapping system was motivated by results of field trials with non-mechanized borehole tapping operations conducted in 1993. Time and motion studies of borehole treatment and container installation using a chainsaw-powered drill attachment and 2-liter PET collection bottle, showed that this system had rather low productivity. Production rates averaged 30 to 35 trees per man-hour, depending upon the type of equipment used and the organization of labor in two-man or three-man crews. Operating cycle times measured in field trials averaged 94 seconds per tree for the 3-man crew to drill 3 holes and install bottles (Table 7.1). Unit operation times for drilling, spraying, installing bottles and moving to the next tree represented 31, 14, 48, and 6 percent of total cycle time, respectively. The imbalance in operating times is a source of inefficiency in this system when organized as a 3-man crew: the sprayer operator was underutilized while the bottle installer was overutilized, and his speed was limiting to the entire crew. The two-man crew suffered from fatigue for one person to perform both drilling and spraying. Sustained work on a full day basis is

probably not possible for any of the crew-equipment combinations observed in this operation. These results showed that both the drilling and bottle installation unit operations were relatively slow, and have a large potential for increased productivity.

Table 7.1. Unit operation times for non-mechanized borehole installation by 3-man crew, field trials at Waycross GA, July 1993.

Unit Operation	Average Time Per Tree (sec)	Percentage of Total Cycle Time
Drill 3 holes with chainsaw powerhead and drill attachment	29.4	31%
Spray chemical with 3 gallon sprayer	13.2	14%
Install 3, 2-liter PET bottles	45.0	48%
Move to next tree (1 man)	6.0	6%
Total cycle time	93.6	100%
Total man-time	105.6	

Mechanized System Design Concepts

Development of equipment for improving productivity of the drilling operation in borehole tapping logically began with the drilling tool itself and considerations of hole size and hole quality. The fundamental objective of borehole tapping is to sever the resin ducts in a cross-sectional area of the tree's sapwood, and provide a pathway for their drainage. Longtime experience in gum resin production by conventional open-face bark-chipping methods had demonstrated that maintaining sharp cutting tools was important for realizing good yields (Clements, 1974). In order to obtain good resin yields, boreholes must be drilled with a clean cutting action to avoid tearing the wood fibers. A USDA-Forest Service study which evaluated different cutting tool designs for drilling in southern pine wood showed that the best holes were obtained with a machine-type double spur, double

twist drill bit (Koch, 1972). This type of drill has cutting edges (spurs) along the outer radius of the bit which cut in a plane tangential to the wall of the hole, thereby severing wood fibers and resin ducts at a favorable angle of attack. The drill bit selected for use in borehole tapping (Irwin 45316) is a machine spur auger bit that features a 15.2 cm double twist with high pitch to facilitate chip removal, a heavy duty shank (1.27 cm dia), and a self-feeding screw point which controls the feed rate and minimizes the thrust force required to advance the drill.

Borehole tapping experiments showed that producing good yields requires sectioning a sufficiently large basal area of the tree to achieve a near-optimal tapping intensity. Large diameter boreholes (3.18 cm) and deep boreholes (> 15.2 cm) did not produce greater yields proportionate to their increased area, because of the diminution in yields per unit area as a function of tapping extent. This suggested that a strategy of drilling multiple relatively small (2.54 cm dia.) boreholes was required for a mechanized system. Drilling larger boreholes to attain the needed hole area was also ruled-out on the grounds of excessive power required, which would have increased the weight and expense of the drilling machine, and increased height of holes in the tree, potentially damaging its value for wood products.

Drilling multiple parallel holes simultaneously by means of a multiple-spindle drill head was the approach adopted for a mechanized tapping system. Multi-spindle drill heads have been widely used in the wood and metal fabrication industries for high production drilling in a variety of patterns, at either fixed or adjustable centers. This approach was preferred to the alternative of multiple independent drilling units, due to lower costs and technological complexity.

Drilling holes individually at a significantly faster rate was ruled out as an option for increasing productivity because of compromised hole quality. The USFS

study (Koch, 1972) showed that better quality holes were obtained when the chip cutting thickness (the drill "bite") was kept small (0.0254 to 0.0508 cm). This implies a bounding relationship between the drill feed rate and drill rotational speed of approximately 10.2 cm per minute per 100 rpm (for a two edged cutting bit). It was observed experimentally that very high drilling speeds (>3000 rpm) can cause excessive heating of the drill bit and "burning" of the hole.

Power required for drilling is a linear function of drill speed and torque, as given in equation 8, where P is power (kw), n is spindle speed (rpm), and T is torque (cm-kg).

$$P=1.587\times10^{7}\times nT \tag{8}$$

Torque for drilling (cm-kg) is related to drill feed rate (f, cm/min), spindle speed (n, rpm), the number of cutting lips on the drill tool (N = 2), and a constant (C) that is specific to the drilled material, as shown in equation 9.

$$T=C\times\frac{f}{nN} \tag{9}$$

Torque and thrust forces reported by Koch (1972) were used to calculate power required for drilling 2.54 cm diameter boreholes with a spur machine-type bit (2 cutting lips), radially in green, high-density, southern yellow pine, for a range of drilling speeds (Table 7.2). The estimated power required for drilling ranged from 0.24 to .92 kw for drilling speeds ranging from 0.84 to 5.08 cm per second. So, a conservative design power for the drilling system is 1.12 kw per drill spindle, or 3.4 kw for a 3 drill system, to allow for losses in power transmission. The power required for thrust is relatively small, and can be ignored.

Table 7.2. Torque, thrust and power required for drilling 2.54 cm diameter holes in pine wood, at different drilling speeds.

Spindle Speed (rpm)	Chip Thickness (cm)	Feed Rate (cm/sec)	Torque (cm-kg)	Thrust (kg)	Power Required (kw)
1000	.025	0.84	17.4	40	0.24
1000	.076	2.54	33.6	60	0.45
2000	.025	1.70	17.4	40	0.48
2000	.076	5.08	33.6	60	0.92

Mechanized Drilling System Construction

The multi-spindle drill head chosen for the mechanized drilling system (RMT-Commander 600, Melrose Park, IL) features three adjustable spindle assemblies which produces a triangular pattern of boreholes with overall widths of 9.5 to 15.2 cm between outer drill centers, and vertical offset of 4.8 to 7.9 cm between the center and outer holes, as shown in Figure 7.1.

The vertically offset pattern was desirable to reduce interference between clustered holes, and was shown to increase yields in tapping experiments (Gainesville, 1994).

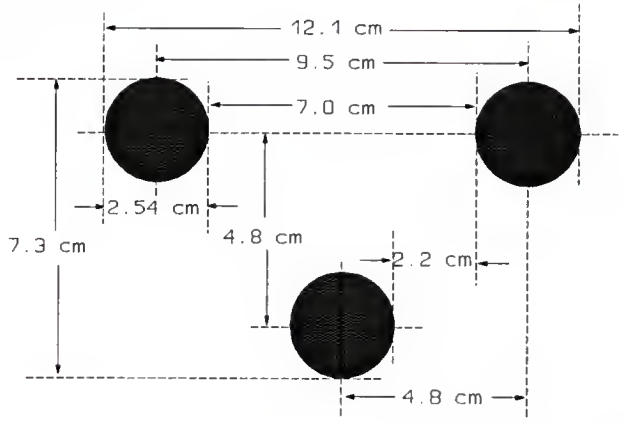

Figure 7,1. Hole pattern produced by multi-spindle drill head.

The drill head was attached to a drill press (Hypneumat SP-312, 30.5 cm stroke, Franklin, WI), that is driven from a double V-belt sheave (12.7 cm dia, type A) on a shaft that runs within the quill feed mechanism. A custom-fabricated steel frame supports the spindle drive motor and precision guide rods for the drill head.

The drilling system was powered hydraulically for both its functions of drill spindle power and drill thrust action. The open-center hydraulic system is provided with independent pressure and flow control for the two circuits through a flow divider (Prince RD-1975-16) and dual directional control spool valves (Husco 5001) with hi and low pressure-relief cartridges. The hydraulic motor (Sunstrand SNM2/25CI06AHH) delivers 152 cm-kg of torque at 1000 rpm when supplied with flow of 38 liters/minute at 14900 kg/cm^2. Shaft power is transmitted from the hydraulic motor to the Hypneumat unit by a V-belt drive with double type-A sheaves in a 4/5 reduction ratio. The Hypneumat drill press provides a thrust force of 544 kg at 2.54 cm/sec when supplied with flow of 3.8 liters/min at 2980 kg/cm^2. A hydraulic gear pump (Sunstrand SNP2/14SCI06) delivers 45 liters/minute at 3300 rpm.

The complete prototype tapping machine as built is shown in Figure 7.2. The drilling system is carried on a two wheel, walk-behind tractor (Gravely Pro model). The Gravely tractor is expected to have a working life of 4000 hours, with proper maintenance and replacement of the engine (Kohler, 6 kw, cast iron) at midlife. Extra large tires (56 cm dia x 25 cm) were provided for the tractor to enable good performance in rough woods conditions. Forward and reverse motion of the tractor is controlled by a single lever mounted on the handlebars that actuates a cone-type clutch. The tractor is equipped with a rotary mower (76 cm dia) that functions to clear a path for the operator and trim vegetation near the base of trees. This heavy-duty mower is gear-driven through a front PTO from the tractor's transmission. The tractor also features drum brakes in each wheel hub, which allow brake-steering of the tractor with a tiller handle, and stabilization of the tractor during drilling with a parking brake.

Figure 7,2--Prototype mechanized borehole tapping machine with multiple-spindle hydraulic drill press, precision sprayer, and spout-bag carrier.

The drilling machine was mounted on the front of the tractor to allow a direct approach to the tree for drilling. A V-shaped guide fashioned from 1.6 cm steel rod serves to position the drilling head at the center of the tree. At the rear of the tractor, the hydraulic pump, reservoir and control valves were mounted on a bracket attached to the tractor's modified drawbar, to counterbalance the added weight of the drilling machine. The pump is driven through a flexible coupling (Woods 5J) attached to a driveshaft on the engine flywheel. A 38 liter hydraulic fluid reservoir was provided for radiative cooling. Hydraulic control valves were positioned on a mast within easy reach of the operator.

The entire machine system was designed to support a one-pass operation for complete borehole installation by a single operator. Liquid stimulant is applied to boreholes with a precision spray gun (Spraying Systems *MeterJet*) that delivers a dose of 1 to 16 ml per shot at 596 kg/cm^2. Spray solution is fed from a 11.4 liter garden type pressurized sprayer tank carried in a bracket on the front of the machine. A large wire basket was mounted on rails atop the tractor's hood to carry a supply of spout-bag collection devices within reach of the operator. An important safety and ergonomic design feature is that all three functions for the complete tapping operation--drilling, spraying, and installing spouts-bags--can be accomplished by the operator from his station behind the machine if the recommended operating procedure is followed.

Spout-Bag Collection System

The concept for an improved collection apparatus for borehole tapping began with the observation that installing 2-liter PET bottles was the single largest unit operation time, representing nearly half of total time per tree (Table 7.1). In

addition, the extremely bulky bottles were difficult to transport in the field. A more compact and easily handled container system was clearly needed.

In 1994, work began with an industry cooperator (Navstoc, Inc., Boca Raton FL), to develop a spout-bag collection apparatus. Plastic bags had been successfully used for collection of gum resin produced by conventional bark-streaking operations. High density polyethylene (HDPE) film bags were proven as strong, durable and leak resistant containers for both the solid and liquid fractions of fresh pine resin. These bags can be manufactured at low cost by a continuous process of extruding a thin film of HDPE material (<0.00254 cm) as a tubular sleeve, then cutting and contact welding to form any size and shape needed. The size of the bag can be easily adjusted to accommodate the maximum expected resin yield, resulting in a highly compact and efficient container system in which the amount of plastic resin used is typically less than one thousandth the volume of the product that it contains.

In conjunction with the plastic bag container, an injection-molded HDPE spout was designed to channel resin from boreholes into the collecting bag. Navstoc Inc. has applied for an international patent on this device. The spout has an overall length of approximately 12 cm, including a tubular outer section that is slightly tapered and sized to fit tightly in a 2.54 cm diameter borehole, and an open lattice-frame inner portion which helps to guide spout insertion and insure adequate hole depth. The outer portion features a flange that seats the spout in the hole, and threads for attachment to the bag at openings between the weldments that form the top of the bag. The spout-bag system was designed to be pre-assembled in the factory with 3 spouts attached to a single bag, and bundled compactly for ready use in the field. To install the spout-bag device, the three spouts are simply inserted

into their prepared holes and firmly pushed with the hand or hammered with a small mallet.

Tests of the Mechanized Borehole Tapping System

The three-hole hydraulic-powered drilling system was first tested in the shop with log sections. Timed high-speed videotape recordings were made of 30 drilling trials to assist in measuring drilling rates and identifying problems through slow-motion replay. A digital photo-tachometer was used to measure and adjust spindle speeds through changes in the belt drive sheave ratios. Further fine-tuning was accomplished through adjustment of hydraulic flow rates with the flow divider valve setting. Pressure settings for the hydraulic circuits were made with permanent in-line gauges. Drilling speeds of 1000 to 1200 rpm were found to work best with the self-feeding auger drill bits.

Cycle times for drilling three 2.54 cm diameter holes to a depth of 15.2 cm in shop tests averaged 13 seconds, including 2 seconds for advancing the bits to contact the log, 7 seconds drilling under load to the full depth, and 4 seconds to retract the drill head. Field tests of the drilling machine on live trees (Gainesville FL, August 1994 experimental plot), resulted in essentially the same unit operating times. Tests with various types of drill bits showed that non self-feeding (screw-pointed) bits required such a large thrust force to advance 3 drills into the wood stock that it was difficult to adequately stabilize the tractor.

The complete borehole tapping machine and spout-bag system was field-tested at a plantation site near Waycross GA (Waycross State Forest) on three occasions in July and November 1994 and February 1995. Continuous timed videotape recordings totaling over 6 hours were made for analysis of the complete borehole tapping installation cycle. The tapping process was broken-down into 4

unit operations: drilling, spraying, attaching spouts and bag, and moving to the next tree. Video records were analyzed upon replay by noting times corresponding to the action defining completion of each unit operation, to the nearest second on the digital display.

Time statistics for the mechanized borehole tapping operation in field trials are presented in Table 7.3. The four unit operations were roughly equally balanced in their share of time, each representing about one fourth of the complete cycle duration. Drilling times averaged 15.7 seconds per tree, representing a 47 percent reduction in time compared to drilling 3 holes individually with the chainsaw-drill attachment (29.4 sec).

Table 7.3. Unit times for high production borehole tapping machine system, Waycross GA, Nov 1, 1994.

Unit Operation	Avg Time Per Tree (sec)	Fraction of Total Cycle Time (%)
Drilling	15.7	27
Apply chemical spray	16.8	28
Install spouts/bags	13.0	22
Travel to next tree	13.7	23
Total time	59.2	100

n = 57 trials

The time for installation of the spout-bag collection device (13 sec) was over 3 times faster than installing 2-liter bottles (45 sec). Travel between trees and applying the chemical spray treatment with the mechanized system was slightly slower than the non-mechanized system. Travel time, averaging 13.7 sec, was the most variable unit operation time, because it depended largely upon forest conditions, including the spacing of tappable trees and the density of impeding understorey vegetation.

Total operating cycle times for the borehole tapping machine system averaged 59.2 sec per tree, which was a 37 percent reduction in time compared to the unmechanized system (106 seconds, Table 7.4). This represented a productivity of about 1 tree per minute, or 60 trees per hour. Using a 90 percent field efficiency factor to account for turning and other necessary maneuvers not documented, the estimated productivity for the machine is 54 trees per hour, a 50 percent increase above the unmechanized system (Table 7.4).

Table 7.4. Comparison of productivity for mechanized and non-mechanized borehole tapping systems.

System	Time Per Tree (sec)	Estimated Productivity (trees per man-hour)
Mechanized	59	54
Non-mechanized	106	39

The recommended machine operating procedure follows six steps: 1) position drilling machine at tree, 2) drill holes, 3) reposition tractor beside tree, 4) apply chemical treatment, 5) install spout-bag, and 6) move to next tree. Because it is necessary to reposition the tractor after drilling the holes in order to allow access to the tree, this step should be completed by moving the tractor so that the operator is in a position to reach the tree from his control station.

General observations of the spout-bag apparatus in Gainesville FL and Waycross GA indicated that it generally performed well, with few instances of resin leakage, but 7 percent of bags had rainwater stemflow leakage indicated by the presence of water in the bags. Most importantly, the experiment conducted at McRae (1994) with paired bottles vs. spout-bag collection devices showed that bags produced 17 percent greater yields than bottles, due to elimination of headspace gas pressure (see Table 5.13). A

possible disadvantage of the spout-bag device is that some volatile terpenes may escape from the container, resulting in attraction of bark beetle pests.

A possible strategy for increasing machine utilization in a mechanized tapping operation is to use a multi-person crew, with several ancillary workers performing the chemical treatment and spout-bag installation, allowing the machine operator to concentrate on the drilling operation. The unit operation times for the mechanized tapping operation (Table 7.3) suggest that two ancillary workers equipped with chemical sprayers and spout-bag carriers would support a well-balanced operation.

Lifecycle Cost Analysis of the Mechanized Drilling Machine

The borehole-tapping machine system represents a new level of technological intensity for the pine resin tapping industry, so it is important to establish its appropriateness through evaluation of lifecycle costs and benefits. Estimated lifecycle costs for the drilling machine system are presented in Table 7.5.

Table 7.5. Estimated 2-year lifecycle costs for the mechanized drilling machine.

First Cost ($12000 for equipment, $2000 for assembly)	$14,000
Salvage value	($1,000)
Net Acquisition Cost	$13,000
Interest Cost (@ 10% per year of first cost)	$2,800
Total Capital Cost	$15,800
Machine Maintenance & Repair Costs (@ 40% of first cost)	$5,600
Total Capital & Maintenance Costs	$20,600
Hourly Capital & Maintenance Cost	$5.15
Hourly Operating costs (fuel & lube)	$0.55
Total Hourly Costs	$5.70
Cost per tree @ machine productivity of 54 trees per hour	$0.106

Acquisition costs of approximately $14,000 include $12,000 for parts and $2,000 for assembly by skilled technicians. An economic life of 4000 hours was assumed for the

machine, with 40 percent of first cost in maintenance expenses. Total lifecycle cost for this machine is estimated at $5.70 per hour, or $0.106 per tree at a productivity of 54 trees per hour (Table 7.5). Direct labor costs for operation of the mechanized drilling system are estimated at approximately $8.00 per hour, giving a total cost of $.25 per tree for labor and machinery.

DISCUSSION AND CONCLUSIONS

Experimental and analytic studies of the borehole resin production system were conducted to support the operational management of this new technology, as the basis for its successful development and commercialization. These studies involved work in the following areas: 1) characterization and conceptual modeling of the fundamental nature of the system, in terms of its structure, function, behavior, and history; 2) measurement and analysis of the productivity of slash pine (*P. elliottii*) in replicated experiments at different sites in its native region in the Southeast US, over period of several years; 3) factorial yield experiments for design and control of optimal tapping treatments; 4) analysis of system behavior over time for scheduling of production operations; 5) assessment of impacts on tree growth, stress, and wood quality; 6) development and testing of mechanized production systems for the drilling, chemical treatment, and collection operations.

Consideration of the ecology and natural history of chemical plant defense systems lead to the conclusion that slash pine is a species uniquely suited to borehole resin tapping by the nature of its specialized strategy for production and storage of non-crystallizing constitutive resin in the tree's stem at relatively high concentrations.

It was previously believed that prolonged resin flow from borehole tapping depended upon the sealed environment provided by the 2-liter PET bottle, such that retention of the volatile monoterpene compounds kept oleoresin in a fluid state, reduced the rate of crystallization, and prevented desiccation of the wounded woody

tissue (Hodges and Williams, 1993). Experimental results, however, showed that an airtight seal actually reduced yields due to increased pressure in a closed container. Cross-species comparisons suggested that the inherent crystallizing tendency of the resin acids rather than the turpentine content is the chemical factor controlling the conductance of oleoresin for borehole flow.

The variable of tree stem size was the single strongest predictor of borehole resin yields, and is a reliable indicator of resource quality for borehole tapping as an economic enterprise. Notably, other forest productivity predictors for gum resin yields, such as tree canopy size, tree growth rate, and forest site index, had substantially lower correlations with resin yield measures. These results indicate that the borehole tapping is primarily a fixed capacity source flow process. Area-specific yields decreased exponentially in relation to intensity of borehole treatments.

The recommended treatment for maximizing yields is to make a set of holes with cross sectional area equal to approximately 35 to 40 percent of the tree's basal area, and apply a CEPA dosage about 0.35 ml (a.i) per tree. Less chemical may be used during the early season to avoid unwanted leaf abscission and tree stress. The tapping intensity can be controlled primarily by the depth of drilling. Vertical spacing between holes takes advantage of interactions between holes from chemical treatment diffusion and water potential changes, to offset the yield suppressing effects of close hole spacings in a mechanized parallel hole drilling system. More research in this area is needed to better characterize patterns of chemical uptake and mutual dosing effects among clustered holes.

Resin flow rates over time were shown to reliably follow an exponential function, with two thirds of flow accomplished by about 50 days, and 90 percent of flow completed by 120 days. Seasonal resin productivity followed a heat-based annual

cycle, peaking during the mid to late summer period (August). Production may be possible for up to 10 months in the southeast US (February to November).

The mechanized borehole tapping system was demonstrated to achieve a labor productivity 50 percent greater than non-mechanized systems, at a lifecycle machine cost of $.11 per tree. Continued technology development should be pursued to increase the speed of the chemical application and spout-bag installation operations, guided by critical lifecycle costing and an understanding of appropriate technology.

Environmental impacts of borehole resin production include the risk of tree mortality due to stress effects, possible insecticide spraying under adverse conditions, and consumption and disposal of plastics used for spout-bag containerization systems. Net consumption of plastics could be substantially reduced by close-coupled recycling the scrap HDPE film materials to make HDPE injection-molded spouts.

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BIOGRAPHICAL SKETCH

Alan Hodges was born in 1959, at the end of the postwar Baby Boom era, and raised in the farm country of the midwestern US. He graduated from high school in Burlington, Iowa, in 1978, having benefited from the fine local public schools, including training in the industrial arts as well as science. He attended the University of Chicago from 1978 to 1982, graduating with a Bachelor of Arts degree in behavioral science. In 1982, he moved to Florida to pursue graduate studies in psychology at the University of Florida. During this time, his childhood interests in agriculture became reawakened. In 1985, he accepted a position with the University of Florida's Food and Resource Economics Department, where he has continued to work to date, in capacities of statistical research assistant and economic analyst. Since 1986, he has been involved with the pine gum resin industry in Florida and Georgia, as a research scientist and technology development specialist, which culminated in this work. In 1985, Alan married Susan B. Marynowski, of Gainesville, Florida, and in 1988, they bought forested land near Hawthorne in eastern Alachua county and built a pole frame house. In 1988, he received a Master of Science degree. As a volunteer community service, he teaches field classes about southern forest ecosystems. His favorite leisure activities are canoeing and wilderness trekking.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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Professor of Agricultural and Biological Engineering

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James W. Jones
Professor of Agricultural and Biological Engineering

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This dissertation was submitted to the Graduate Faculty of the College of Agriculture and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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